A Hydrodynamic Perspective on RHIC Phenomena

BROOKHAVEN NATIONAL LABORATORY

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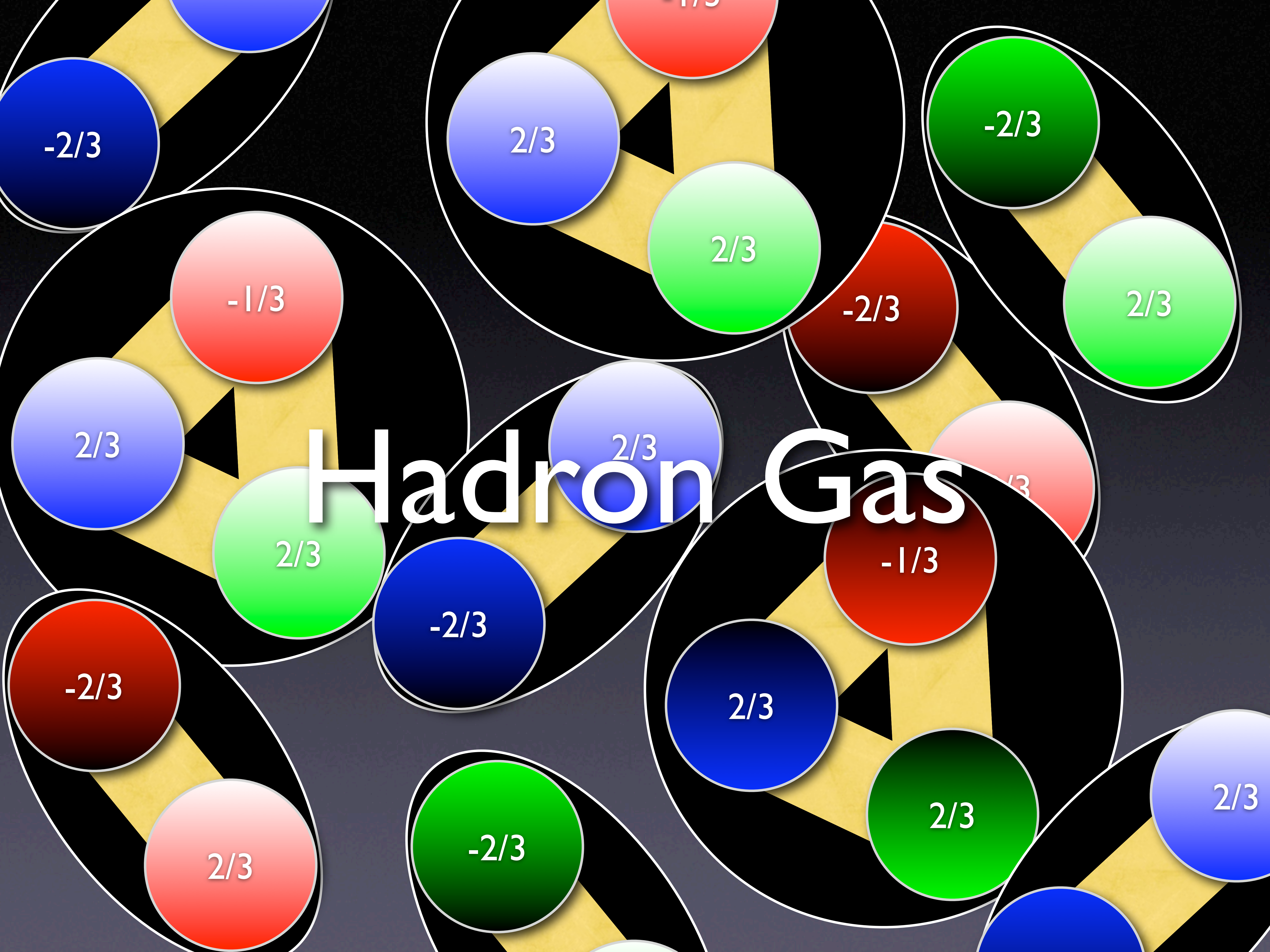
OSU Seminar, 3/7/2006

Murray & Me

Born 1929
Yale, JE '48
PhD, MIT '51
Invented quarks

Born 1969
Yale, JE '92
PhD, MIT '98
Studies quarks

Hadron Gas

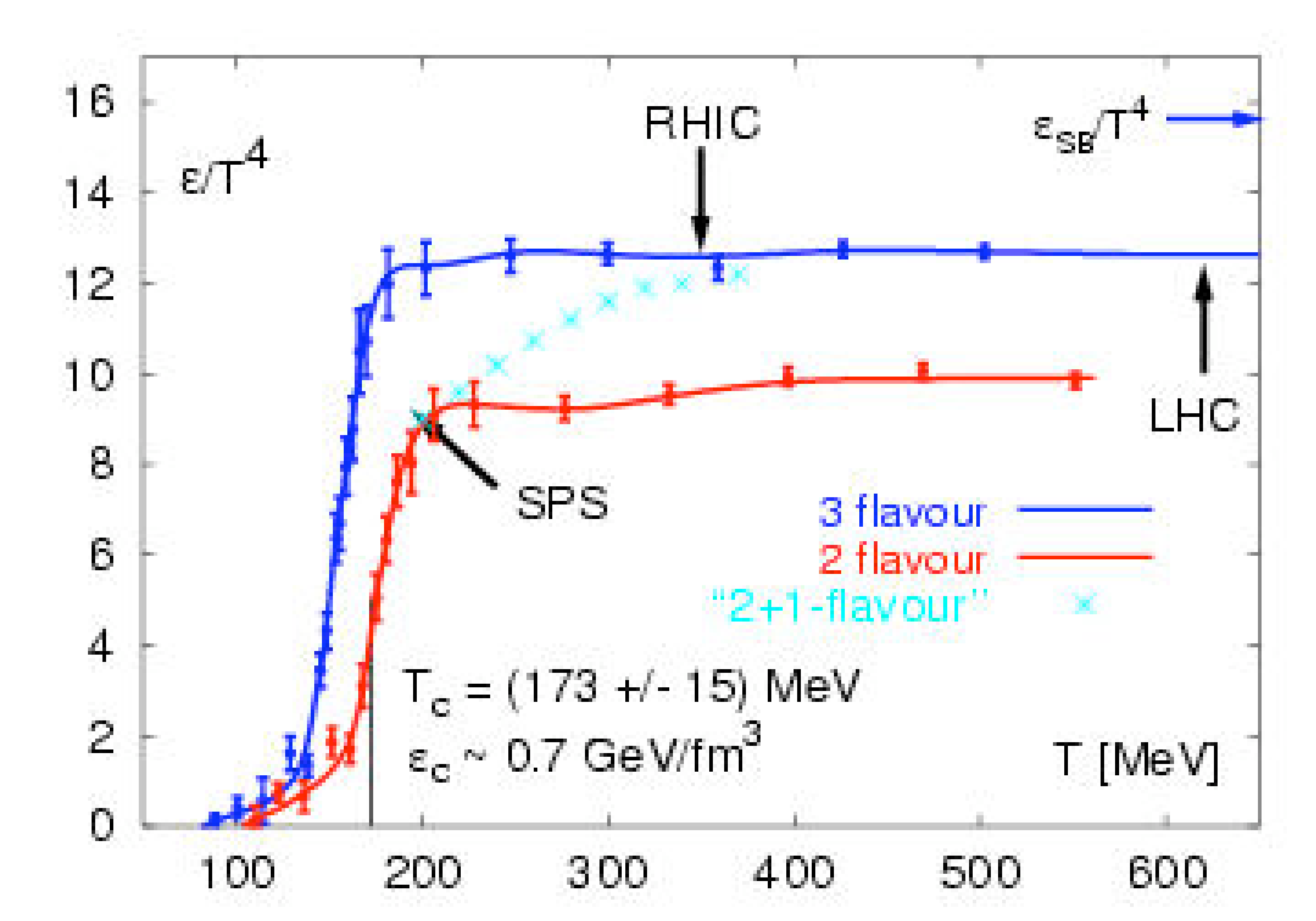


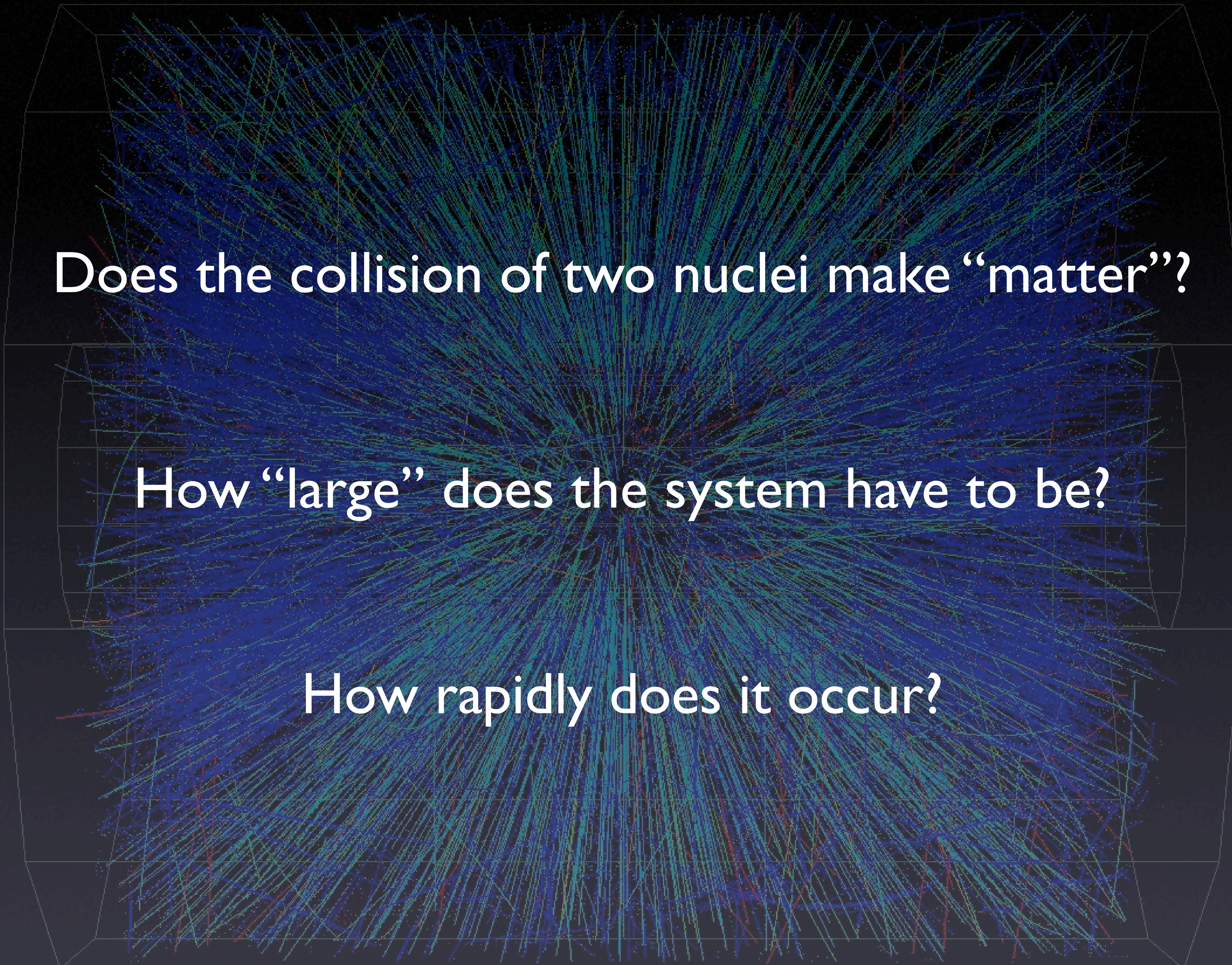
Quark-Gluon Plasma

Strongly Coupled QGP

Information From Lattice

$$\epsilon_P = \frac{M_P}{V} \sim 500 \frac{MeV}{fm^3}$$



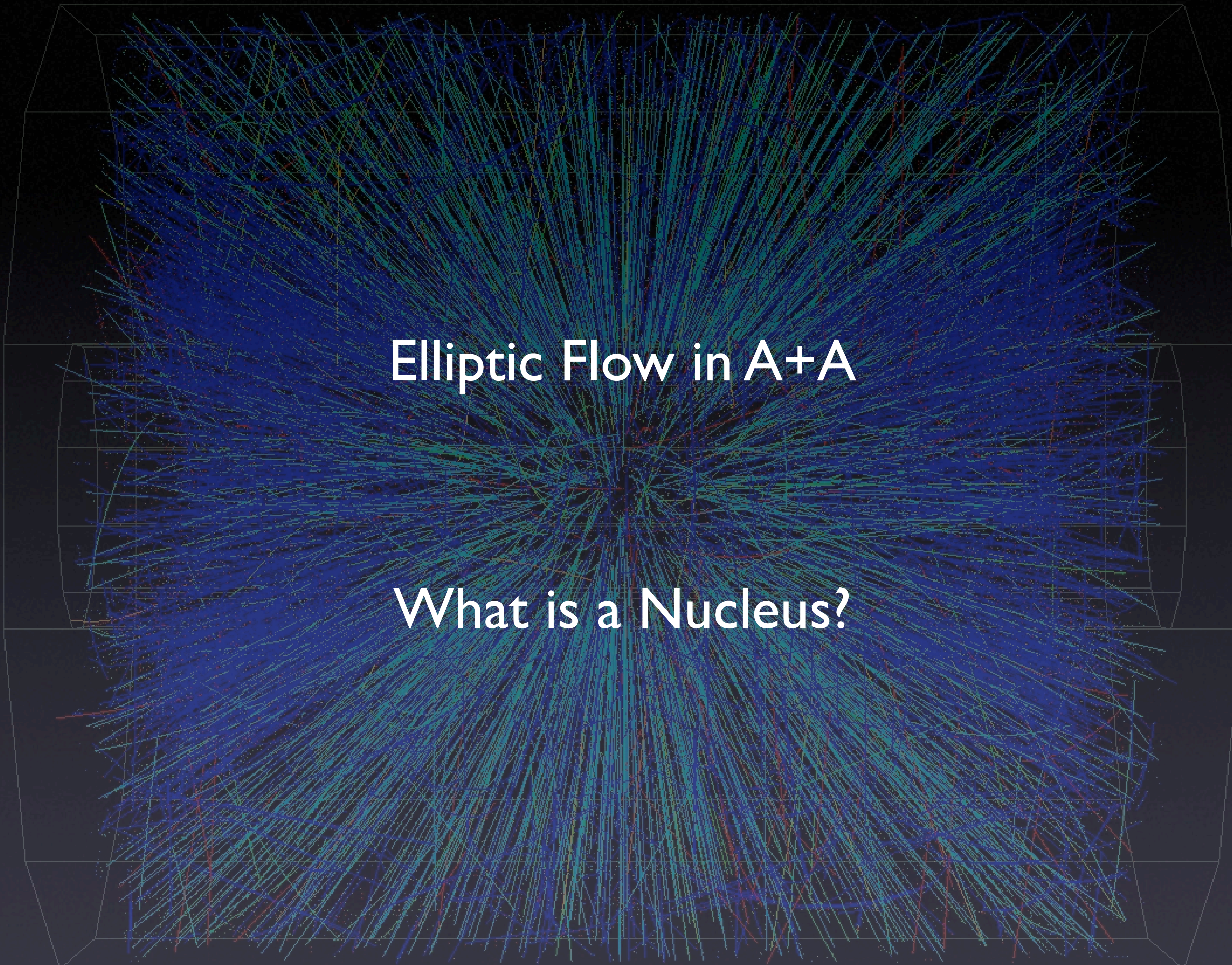


Does the collision of two nuclei make "matter"?

How "large" does the system have to be?

How rapidly does it occur?

- Elliptic Flow
  - “Participant Eccentricity”
- Longitudinal Flow
  - Surprises in Landau Hydrodynamics
- Is there thermalization in elementary reactions?
  - A+A vs. e+e- revisited: role of baryon density
  - HBT systematics in p+p, d+Au
  - Longitudinal “shifts” in d+Au
- What is the relevant energy density?

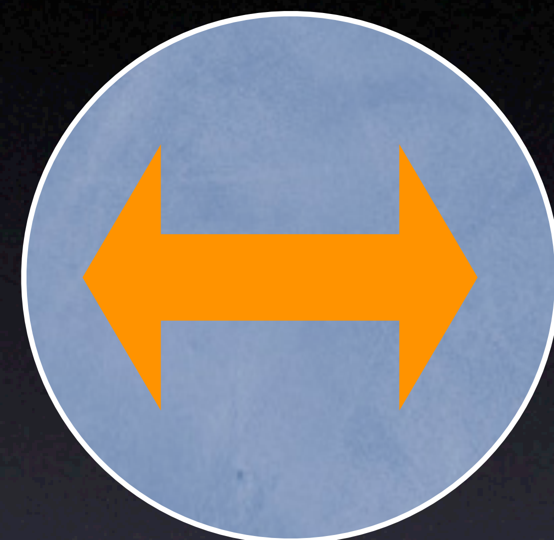


Elliptic Flow in A+A

What is a Nucleus?

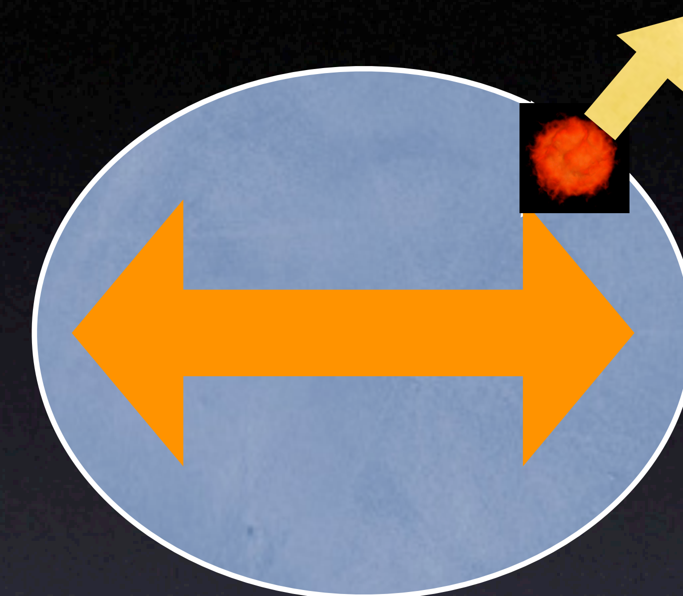
What is "Hydrodynamics"?

Energy density thermalized in a volume, adjacent cells are in causal contact



Presure gradients develop via expansion into vacuum

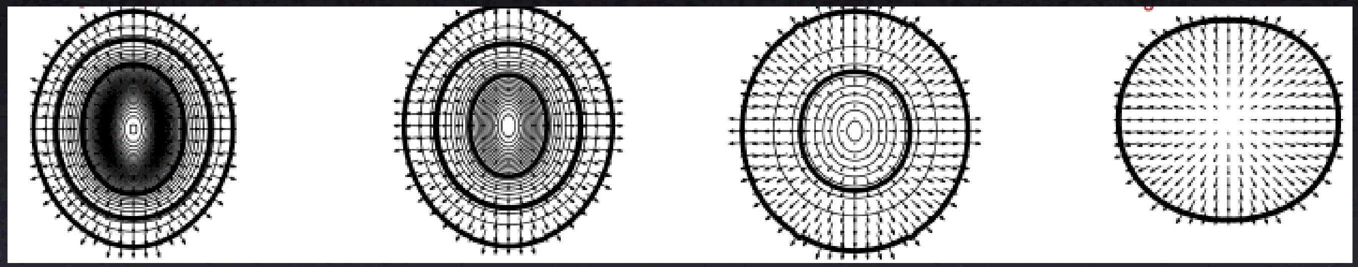
$$\partial_\mu T^{\mu\nu} = 0$$
$$P = \frac{\epsilon}{3}$$



When local temperature falls below some T_c interactions turn off and fluid cells "freeze out" as isotropic fireballs (in fluid rest frame)

Implications

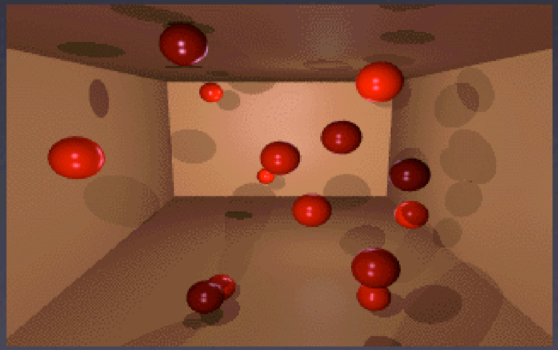
Hydro evolution deals with transport of energy & momentum (and conserved quantum numbers): only EOS carries info on DOFs

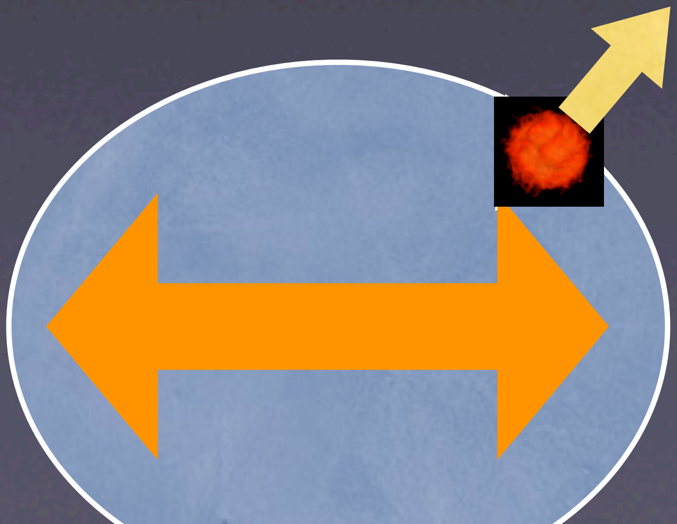


(Heinz/Kolb)

Not meaningful to speak of "particles" before they freeze out as asymptotic states

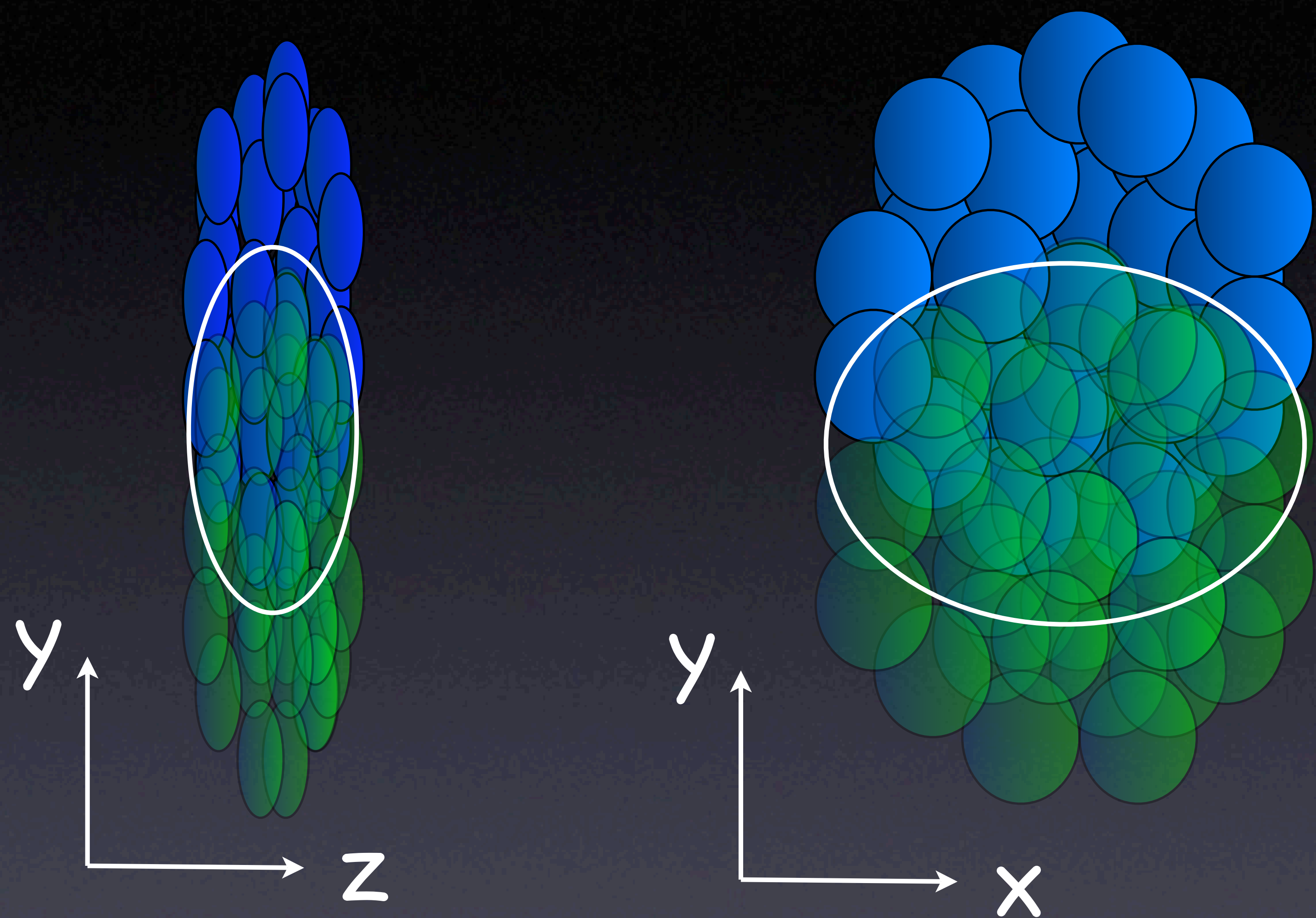
Potentially a mistake to interpret the final state multiplicity as the "N" particles in a box (when a system is too small to show hydro?)





In this picture, the freezeout temperature is a fundamentally <u>local</u> property of the dynamics (i.e. it's not the temperature of <u>the</u> system)

“Shapes” of Things

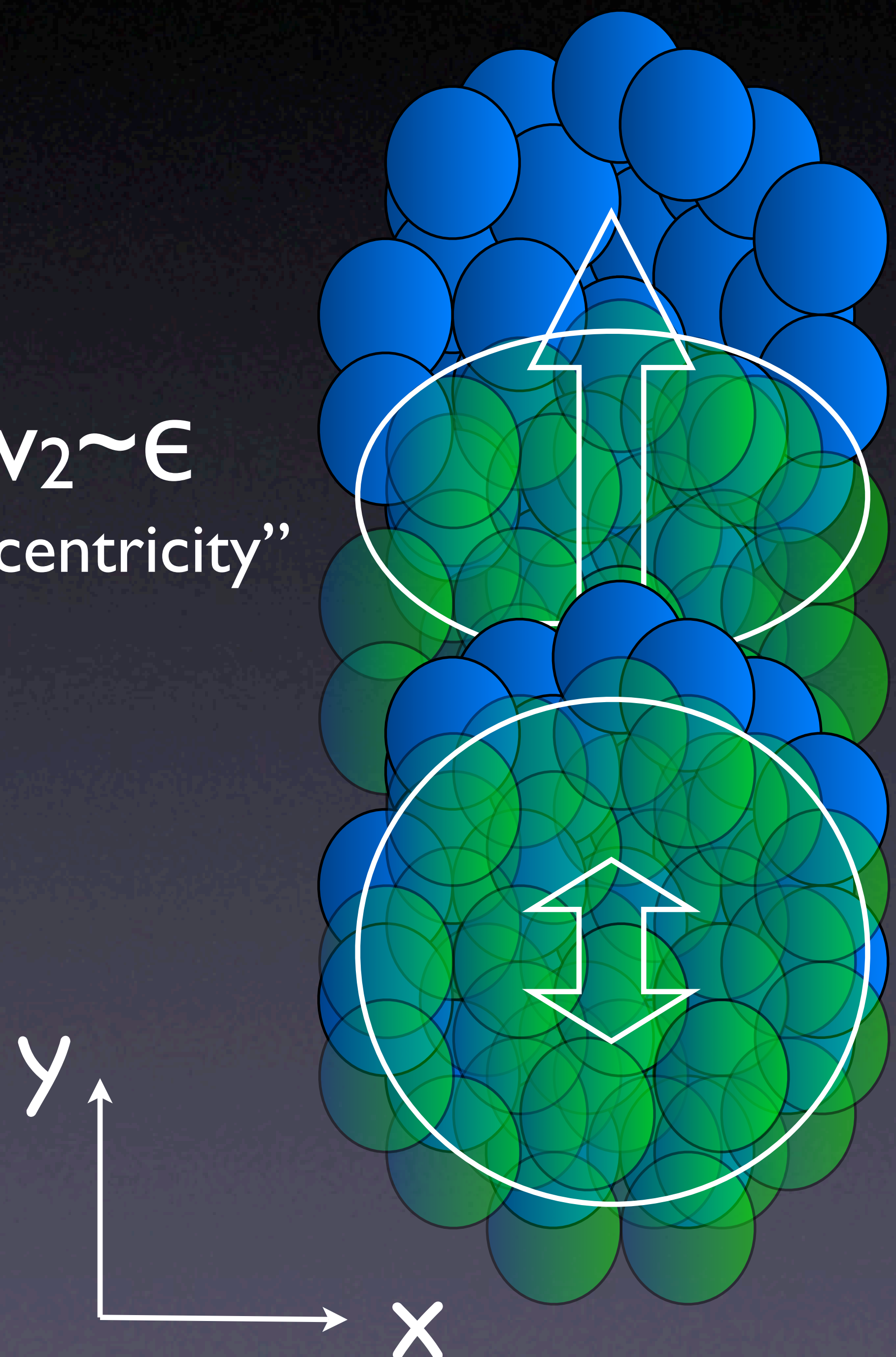


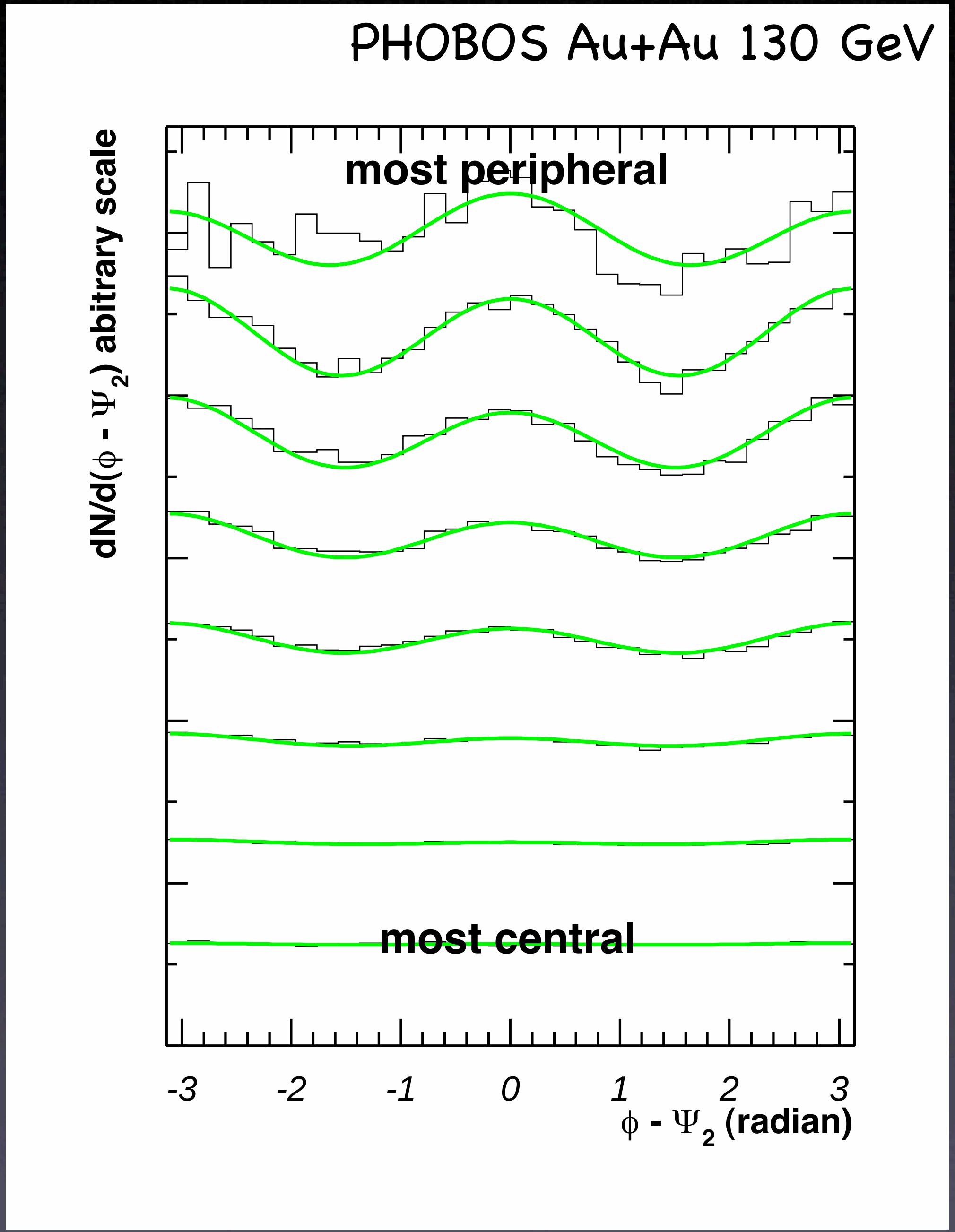
RHIC collisions have a special shape:

1. Compressed along the beam directions
2. Almond shaped in the “transverse” plane

“Elliptic (Transverse) Flow”

$v_2 \sim \epsilon$
“eccentricity”





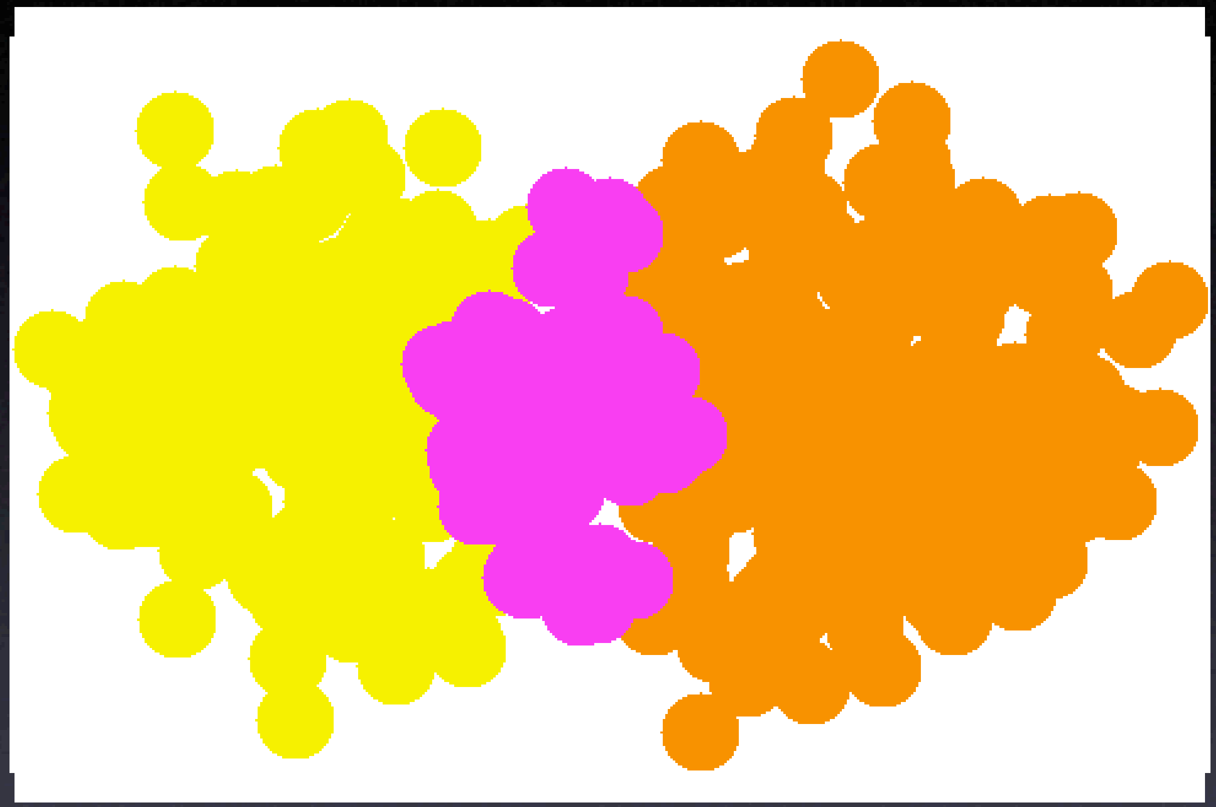
Extract
“v_2”

Modulation in the angle in the transverse direction

What is “eccentricity”?

This section relies on work by:
M. Baker/BNL,
C. Loizides/MIT,
R. Bindel/UMD,
P. Walters/UR

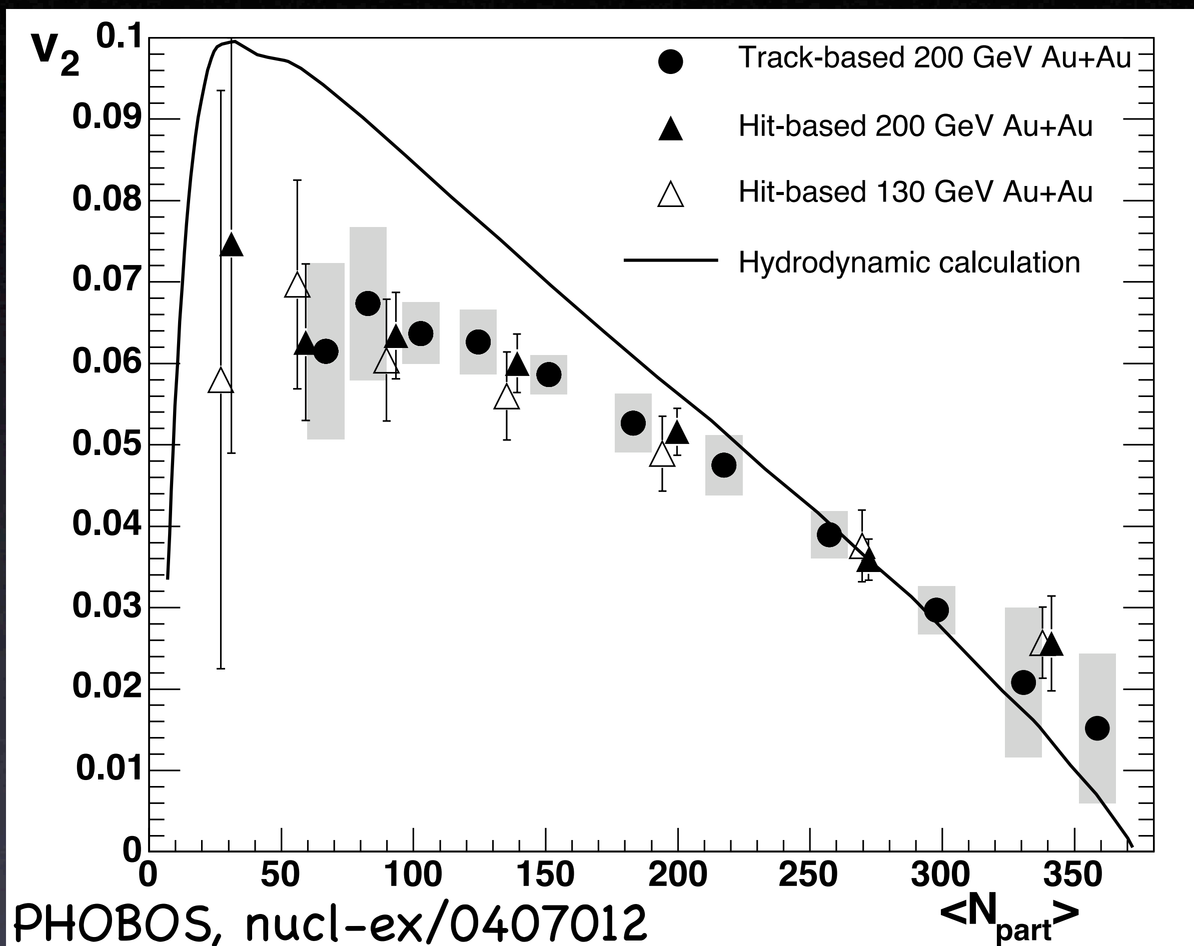
and talks by
G. Roland/MIT,
S. Manly/UR,

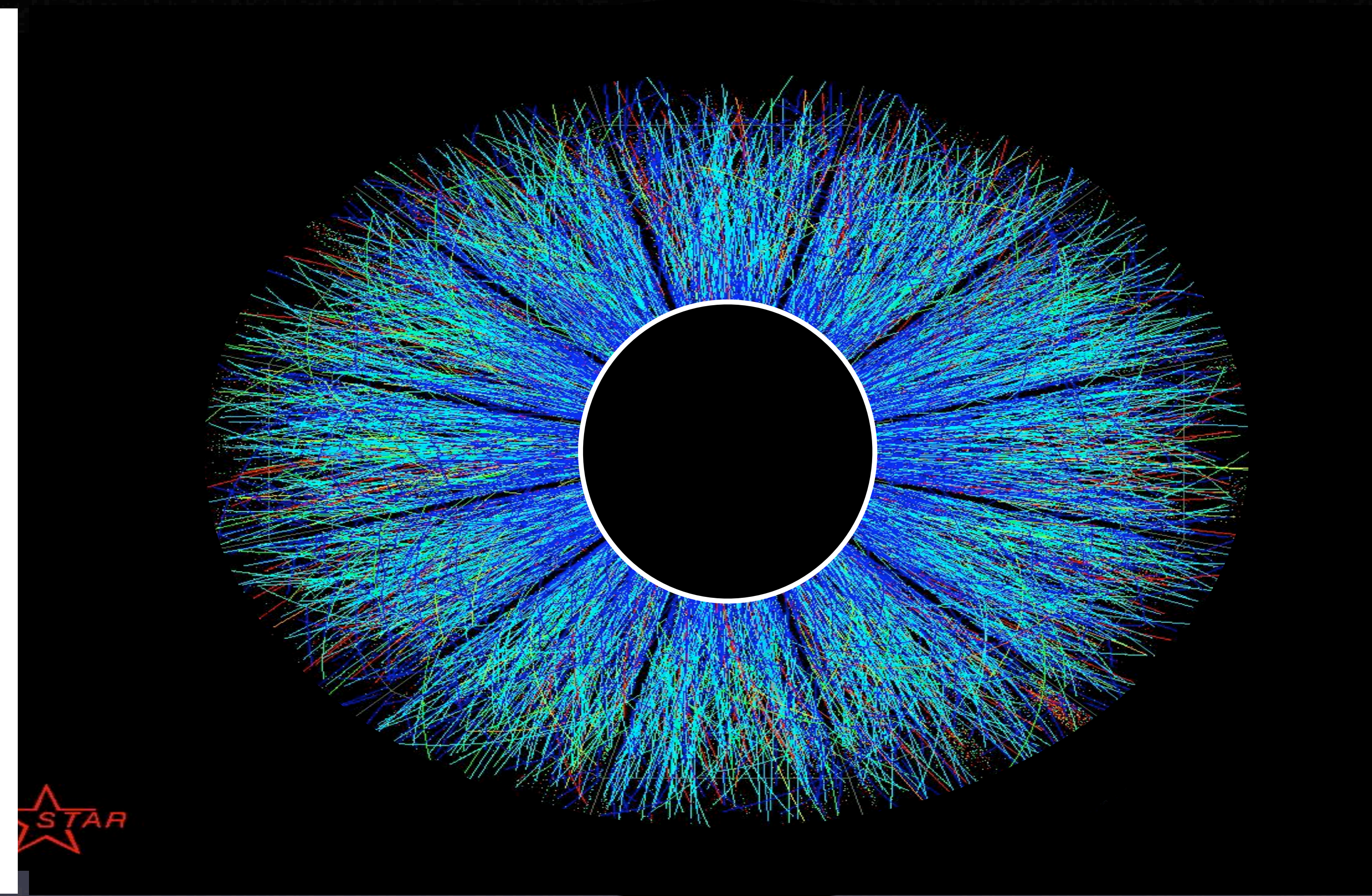


$$\varepsilon = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}$$

Eccentricity characterizes elliptic shape of overlap
(simple to think about w/ continuous densities, but...)

Agreement with Hydro

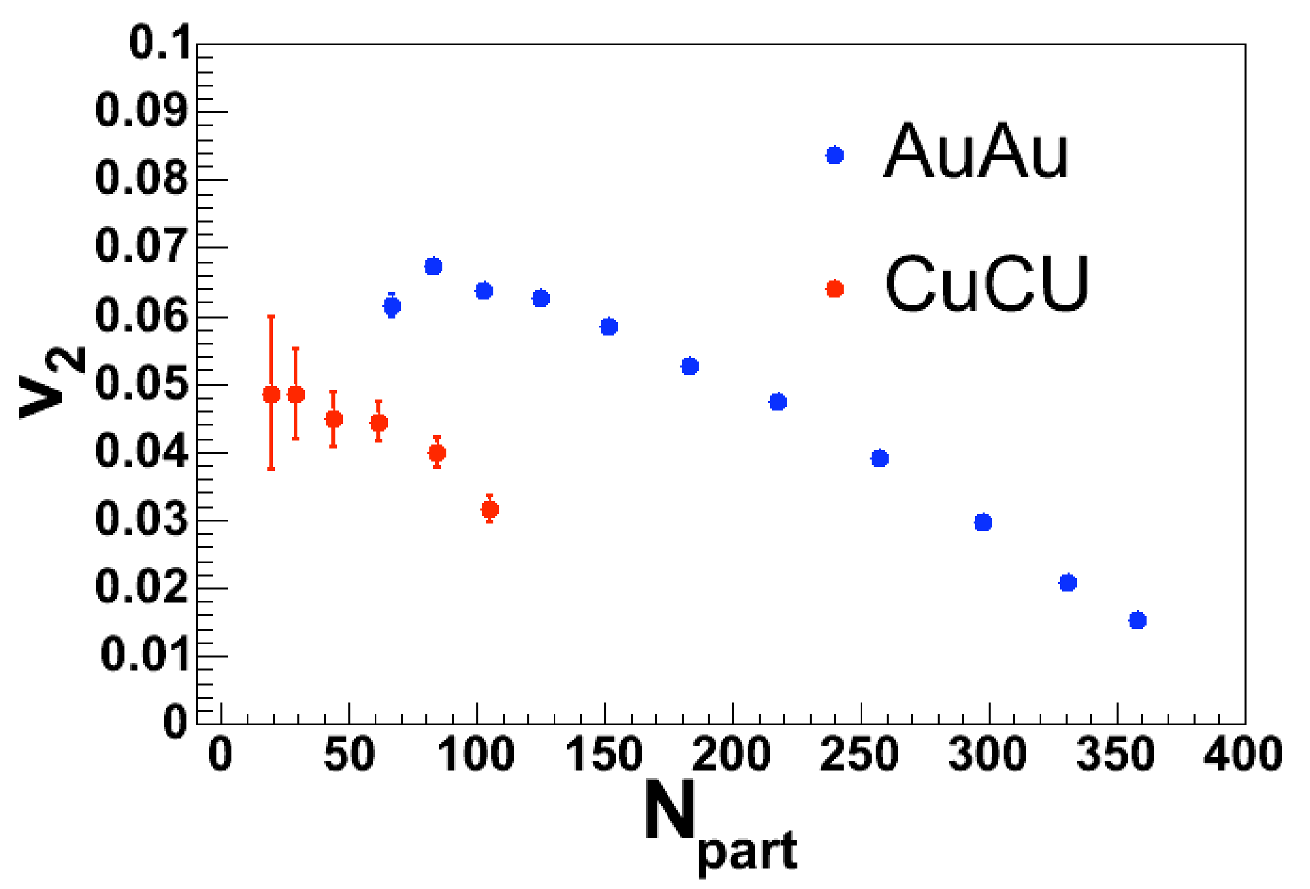


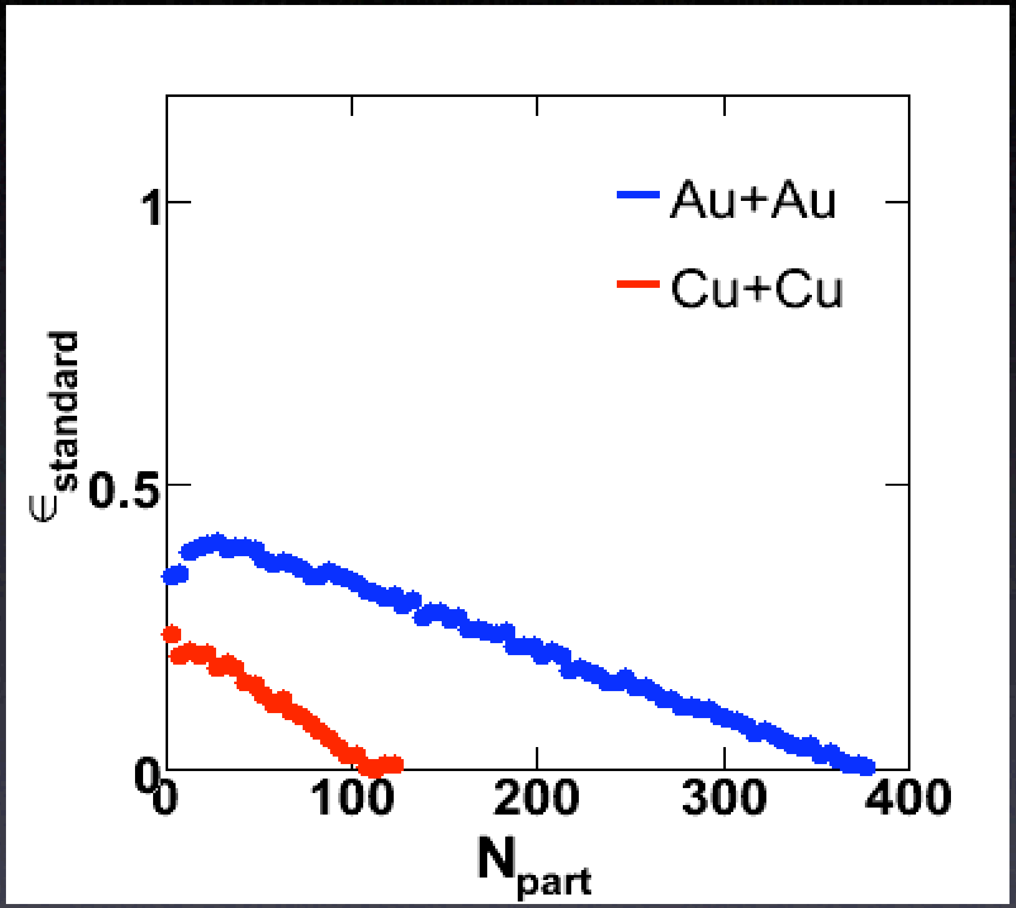


$$\frac{1}{N}\frac{dN}{d\phi} = 1 + 2v_1 \cos(\phi - \Phi_R) + 2v_2 \cos(2[\phi - \Phi_R]) + \ldots$$

Agreement with calculations of asymmetries, based on ideal fluid thermalizing in t~0.6fm/c

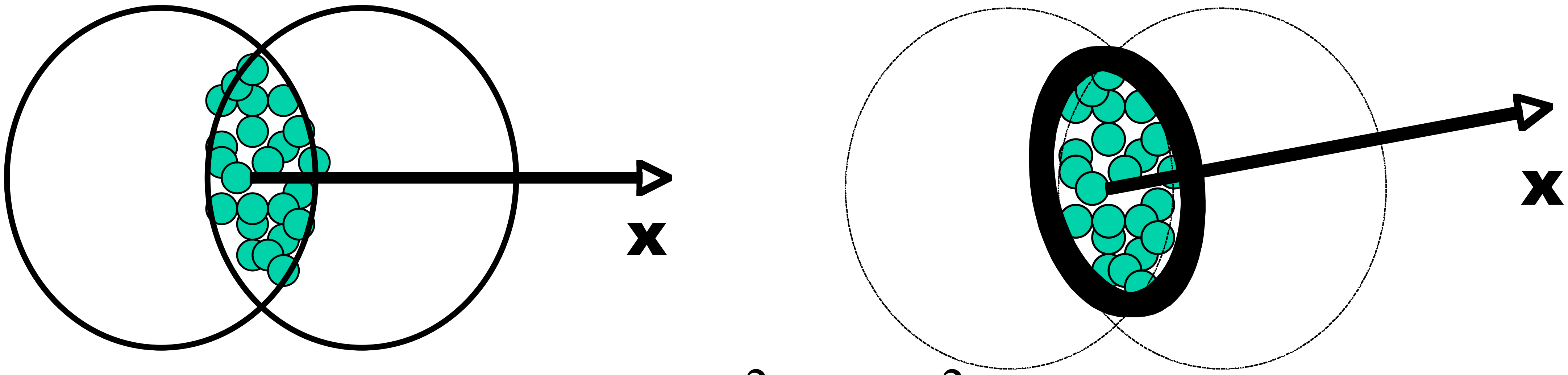
Au+Au vs. Cu+Cu





While Au+Au shows a similar trend in measured v_2 and calculated ϵ,
Cu+Cu trends look very different

Defining “Eccentricity”

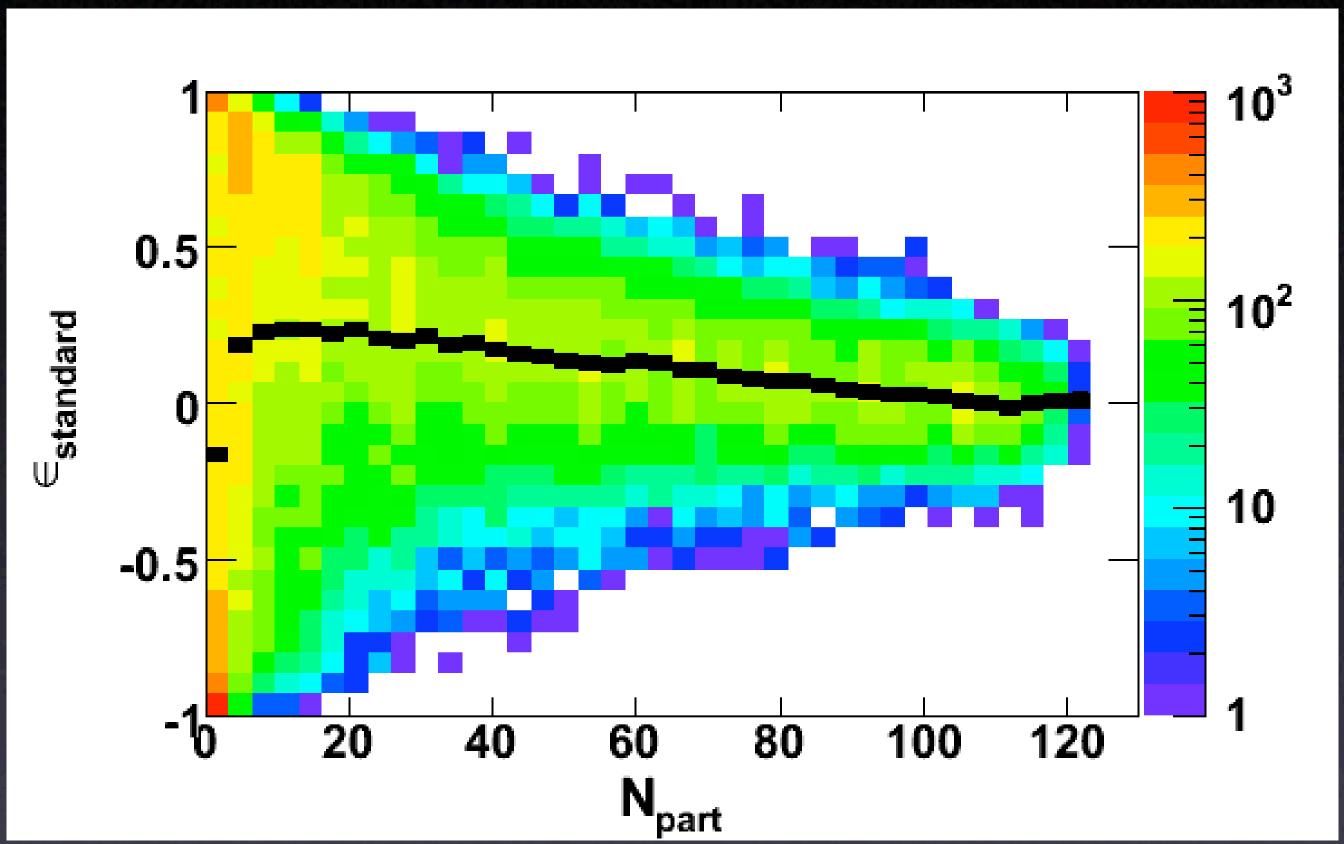


$$\varepsilon = \frac{\sigma_y^{\ 2} - \sigma_x^{\ 2}}{\sigma_y^{\ 2} + \sigma_x^{\ 2}}$$

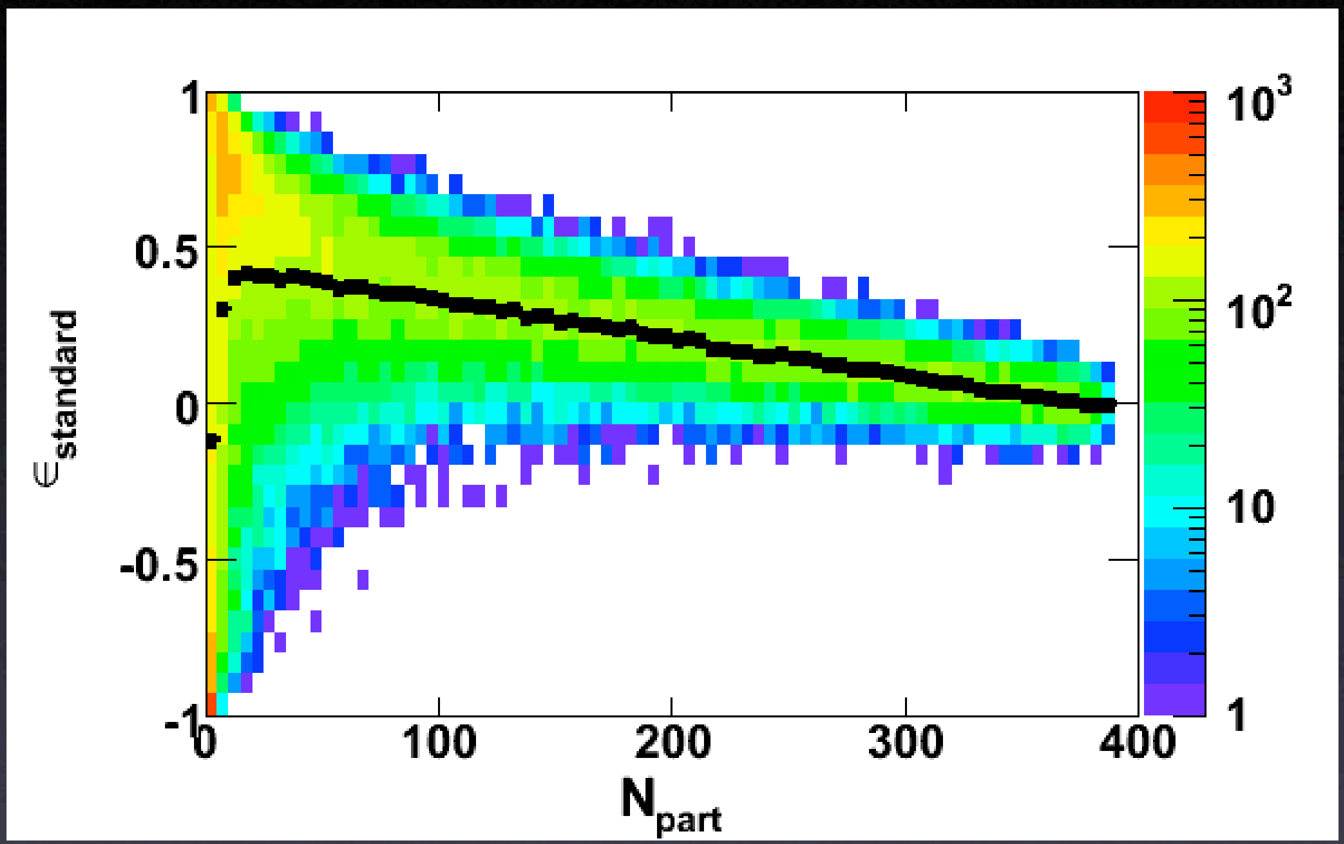
1. relative to assumed reaction plane.
2. relative to “principal axes”

$$\epsilon_{part} = \frac{\sigma_y'^2 - \sigma_x'^2}{\sigma_y'^2 + \sigma_x'^2} = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4(\sigma_{xy}^2)^2}}{\sigma_y^2 + \sigma_x^2}$$

Standard Eccentricity

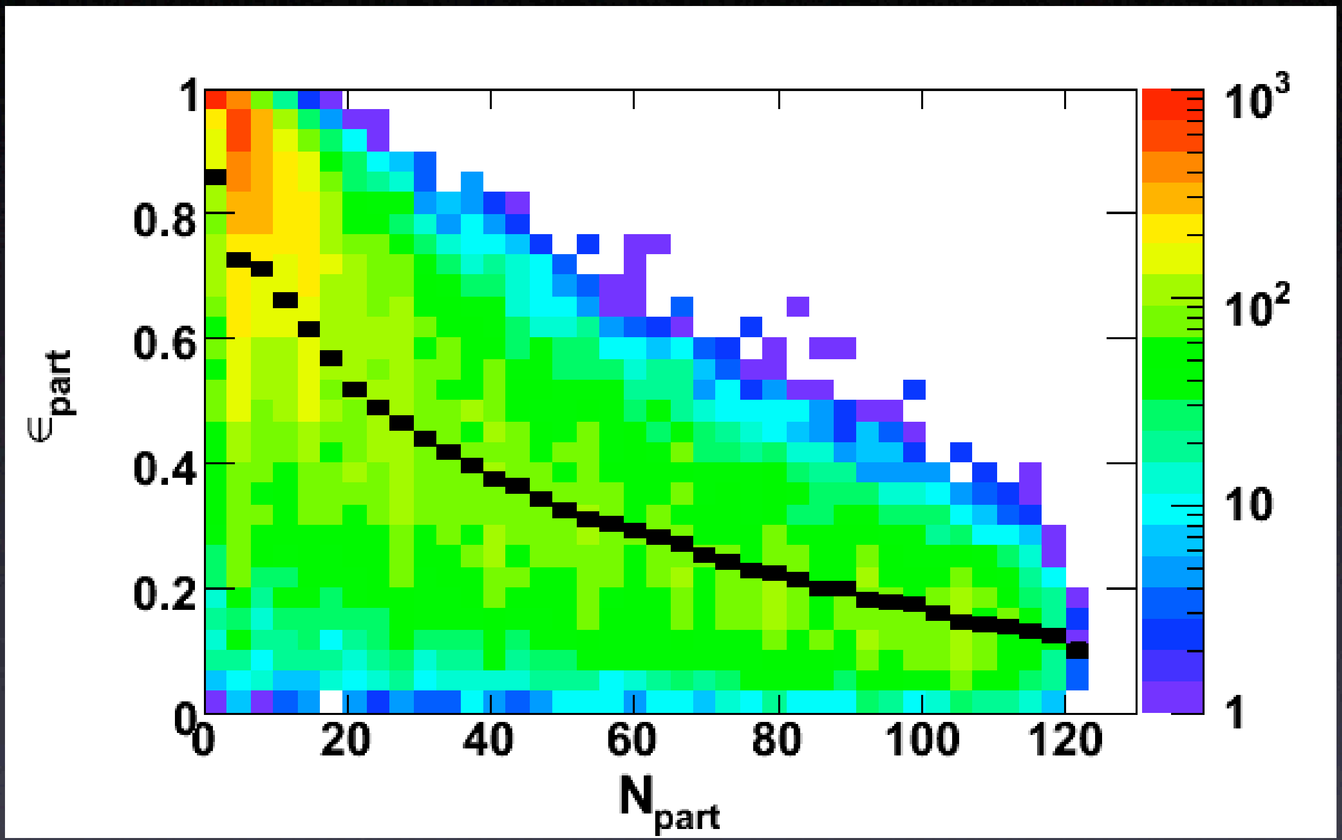


Cu+Cu

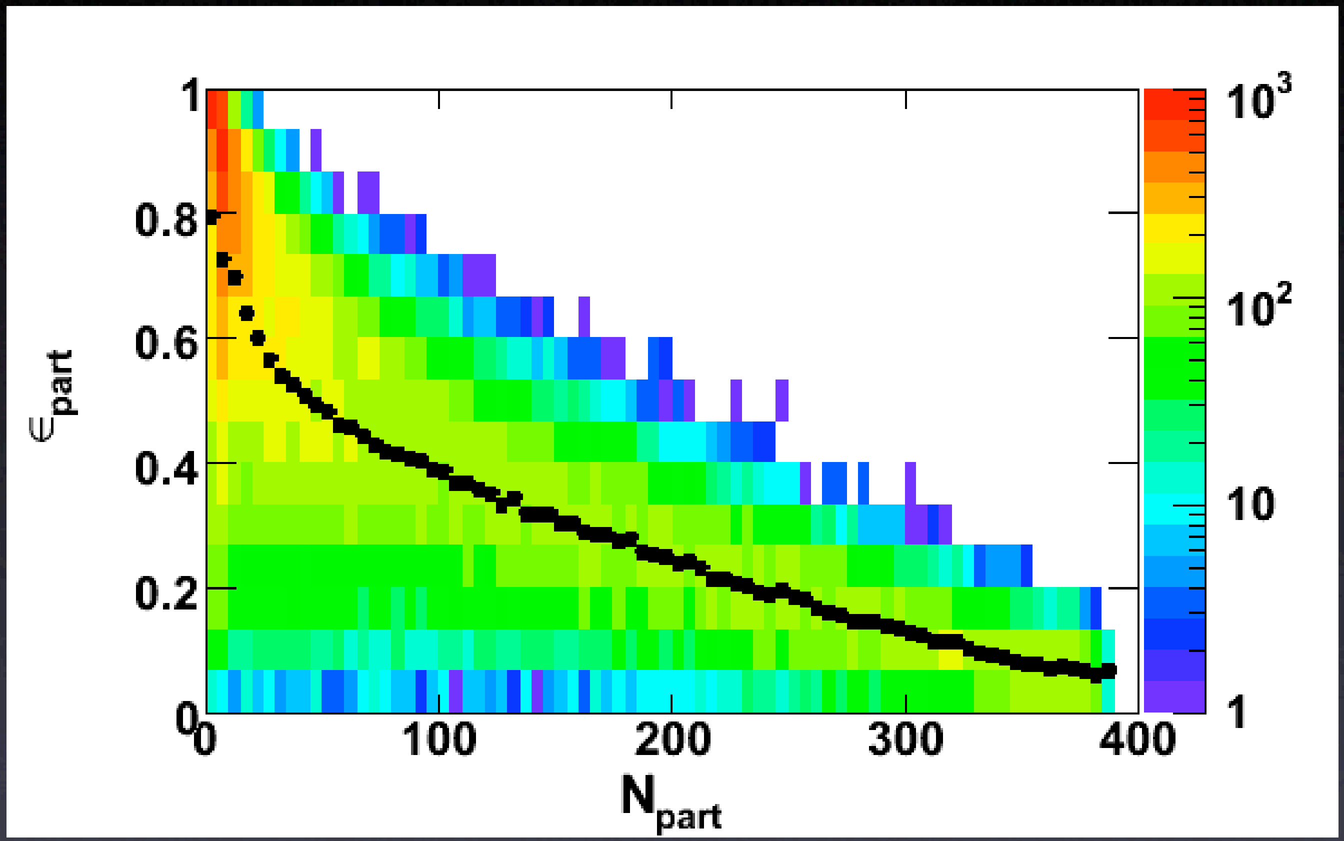


Au+Au

“Participant” Eccentricity

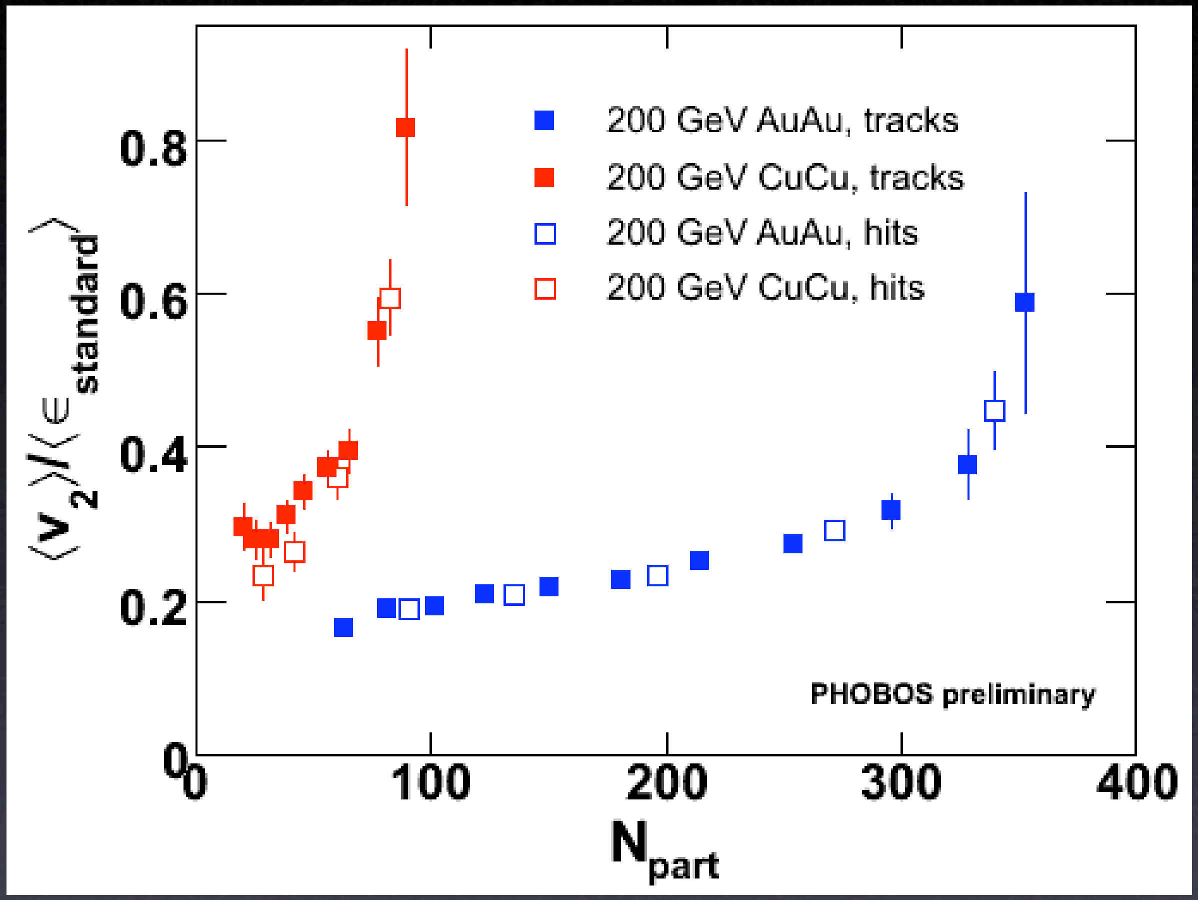


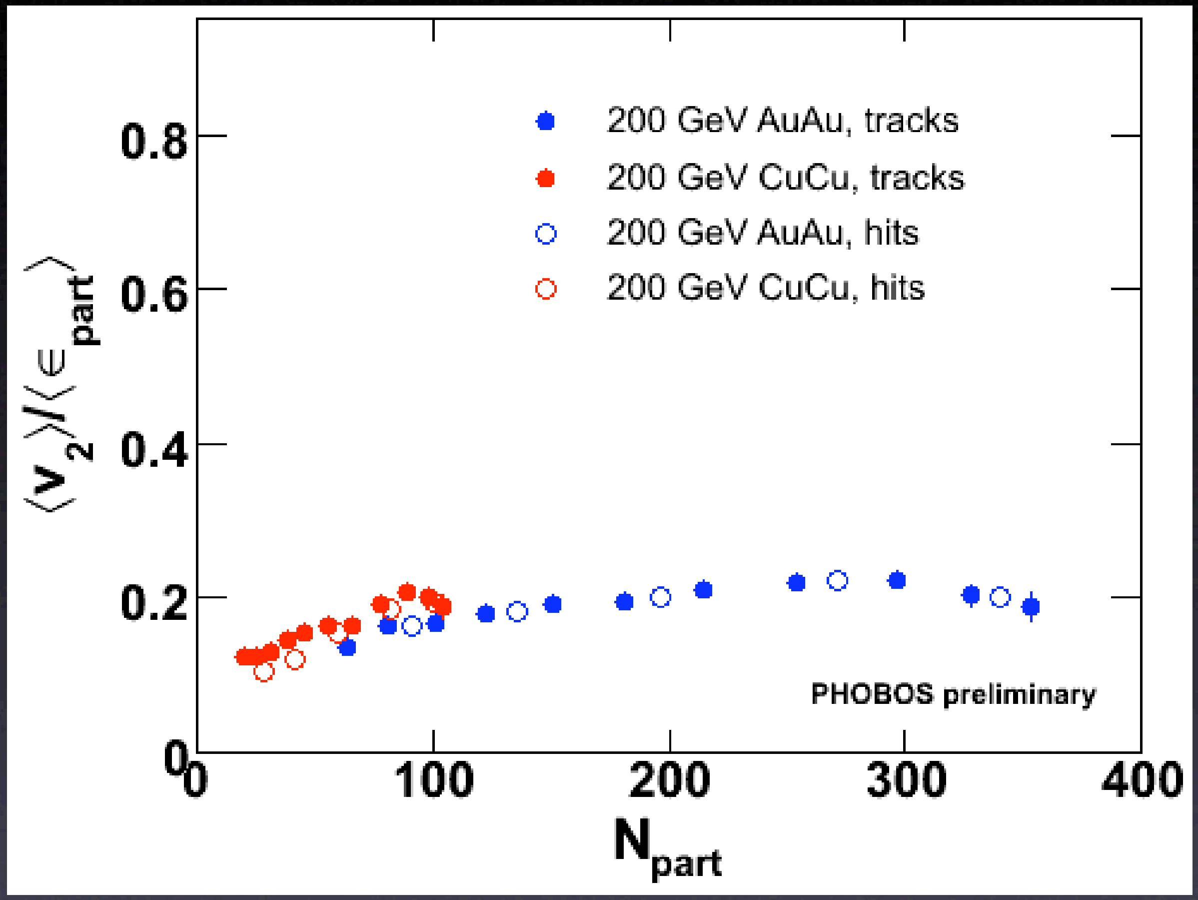
Cu+Cu



Au+Au

Comparing Au & Cu



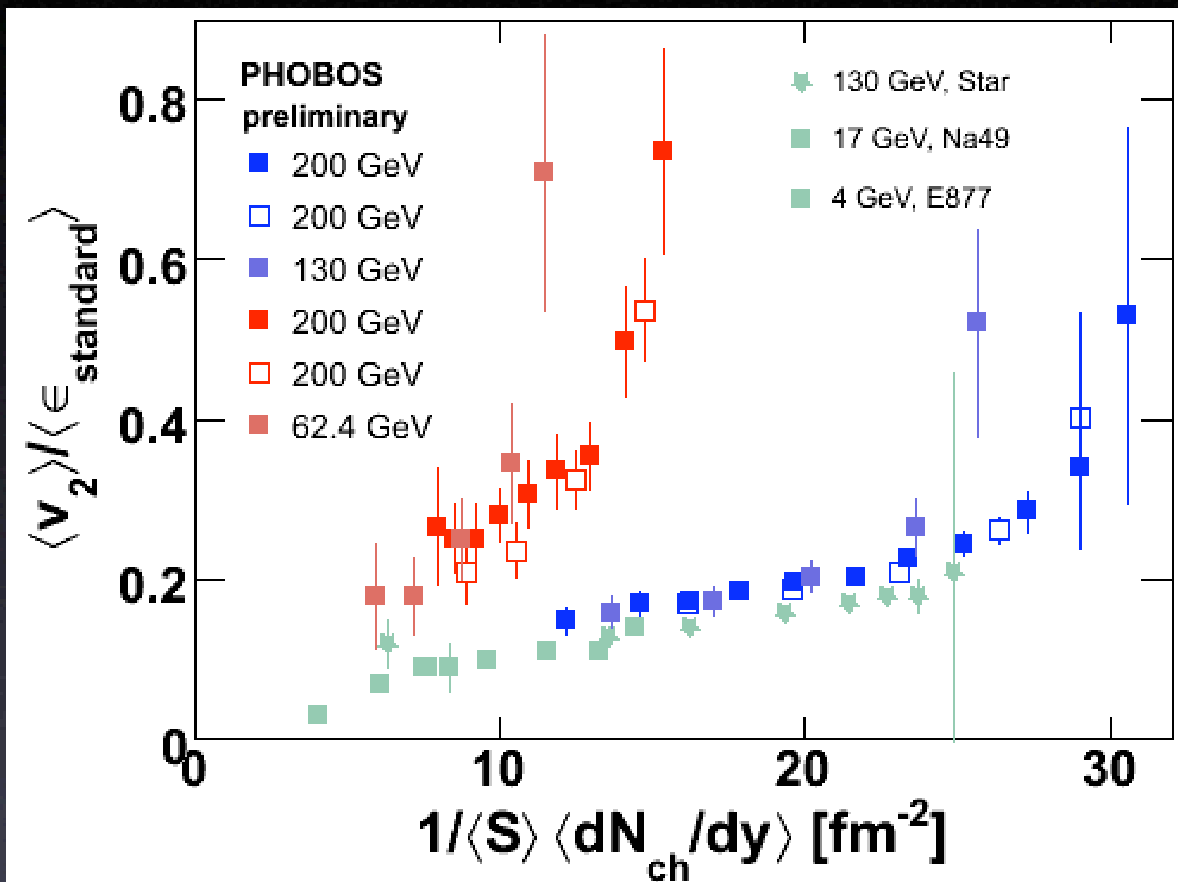


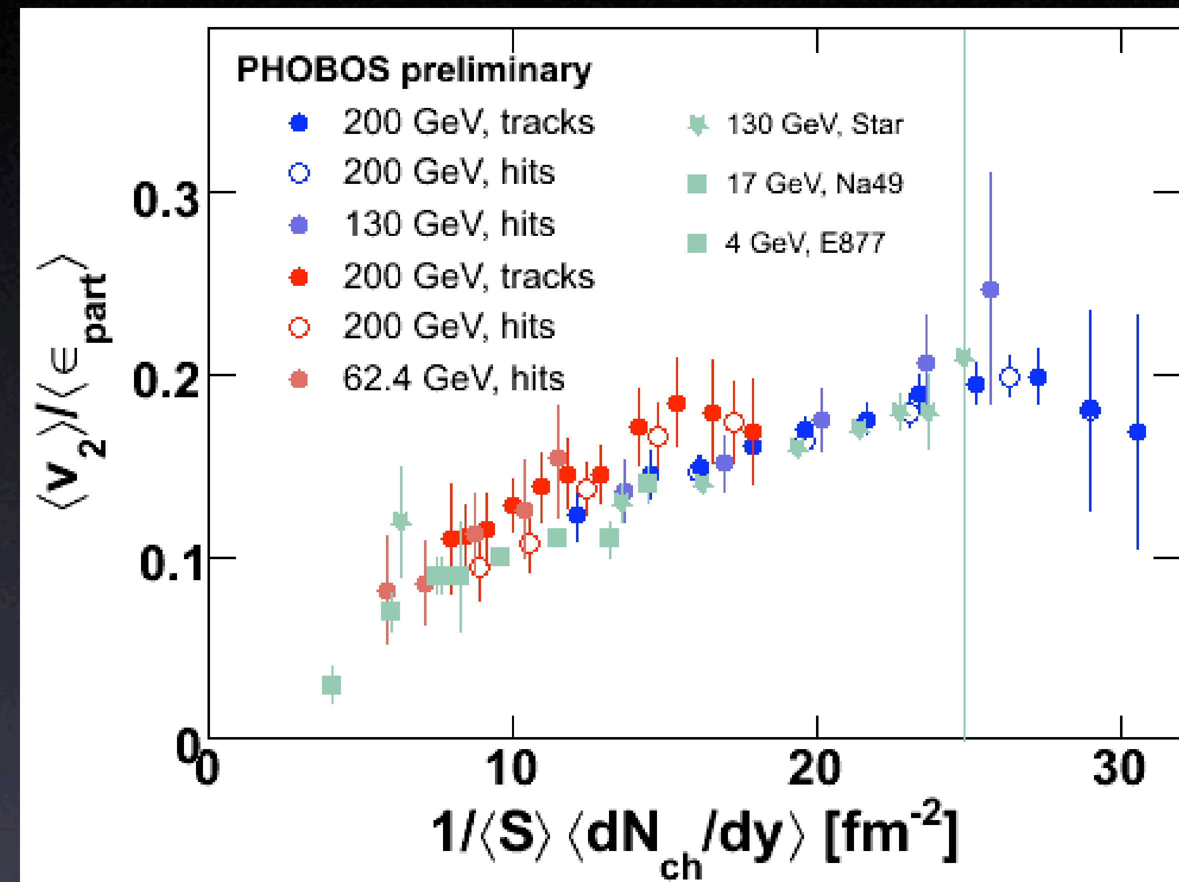
v_2 is expected to scale ~linearly with eccentricity

standard eccentricity doesn't show connection

participant eccentricity both flattens trend vs. Npart and "matches" Au+Au and Cu+Cu

"Voloshin" Plot





"Low density limit" gives result that

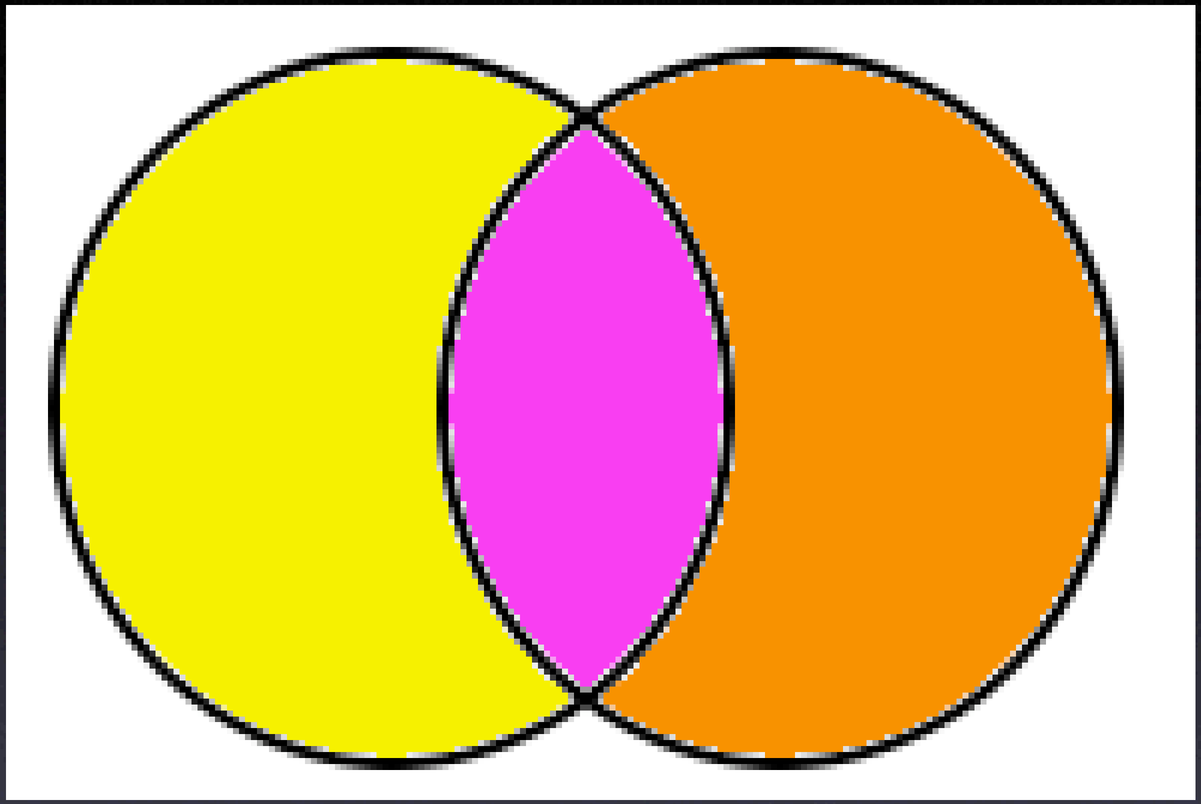
Coupling of pressure to geometry

$$\frac{v_2}{\epsilon} \propto \frac{dN/dy}{S}$$

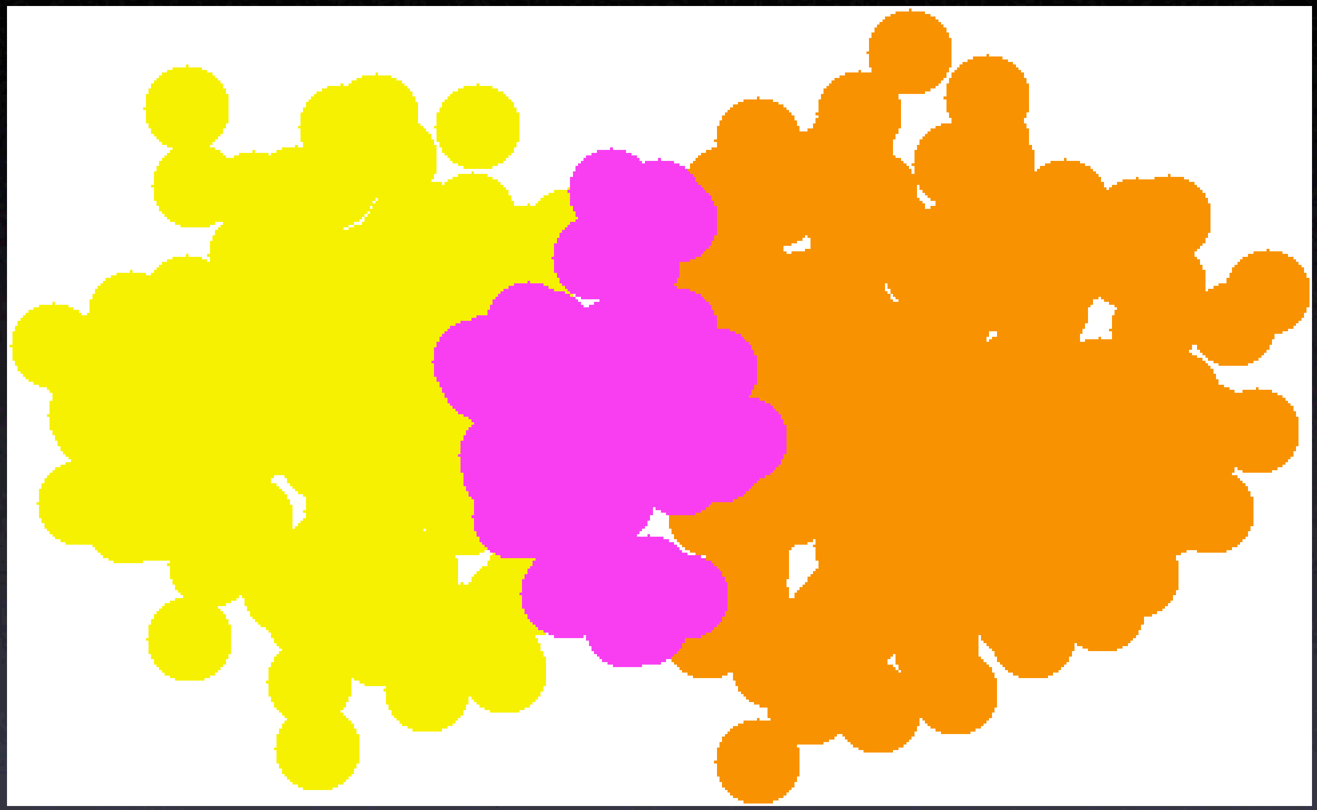
Areal particle density

"matches" only with participant eccentricity

What is a Nucleus?



Smooth matter density?



Clumpy bag of nucleons?

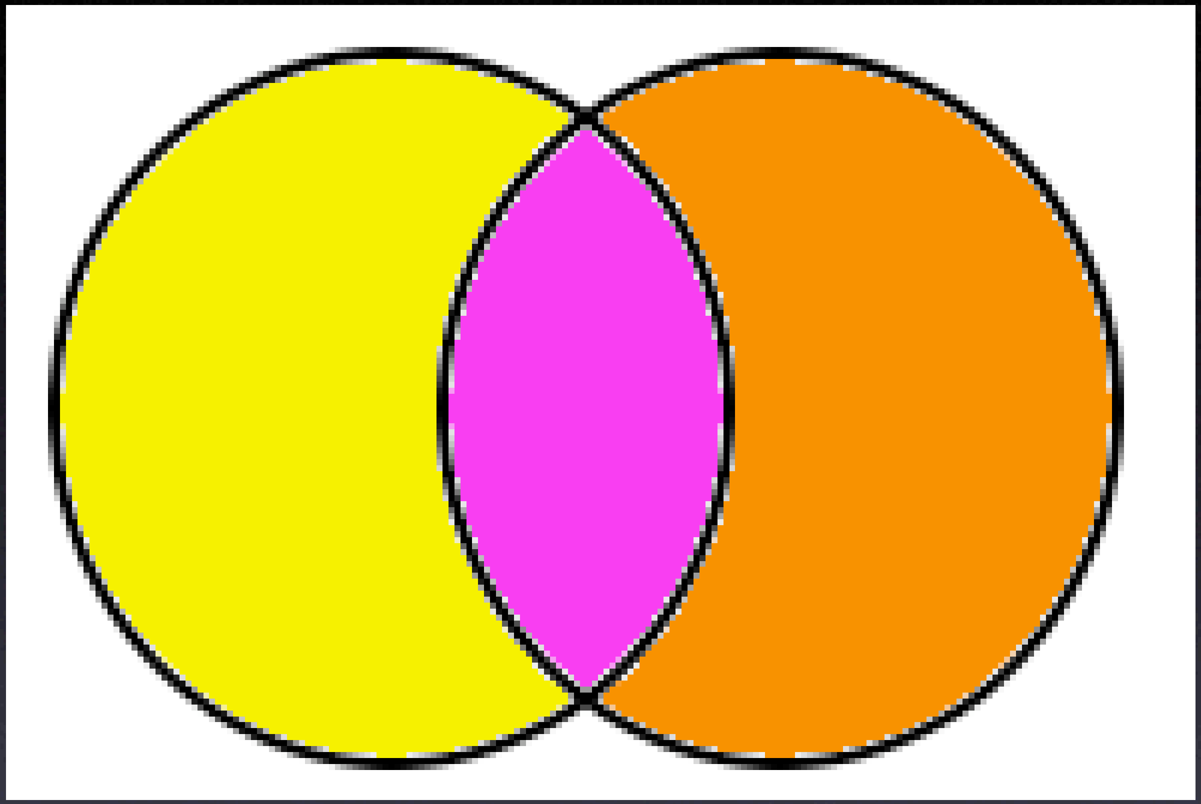
Our data seems to prefer the clumpy bag, but many nuclear physicists express strong misgivings

Adapted from G. Roland, MIT

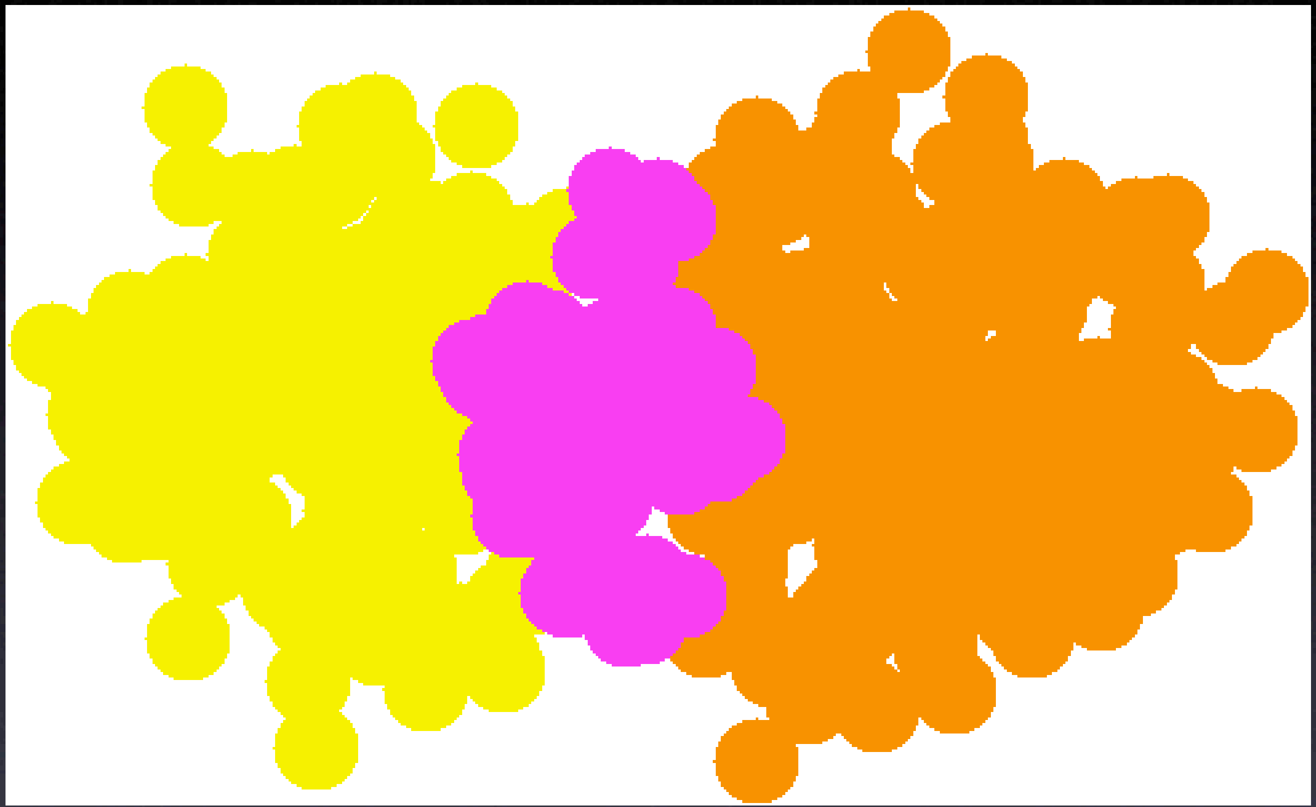
FAQ

- Sensitivity to Glauber parameters
  - varied σ from 30 to 46 mb
- Nucleons in same nucleus can't sit on top of each other
  - introduced inter-nucleon separation d; varied d from 0-2fm
- Centre of gravity fluctuates in Glauber
  - small smearing of b-distribution
- WS parameters come from probing charge distribution
  - check contribution of 'stray' nucleons to eccentricity - small effect
- Nuclei "known" to be smooth
  - Aren't we sampling a very short time?
- This Glauber approach violates QM mechanics & known nuclear physics
  - No fermi momentum, no collective oscillations

When is a Nucleus?

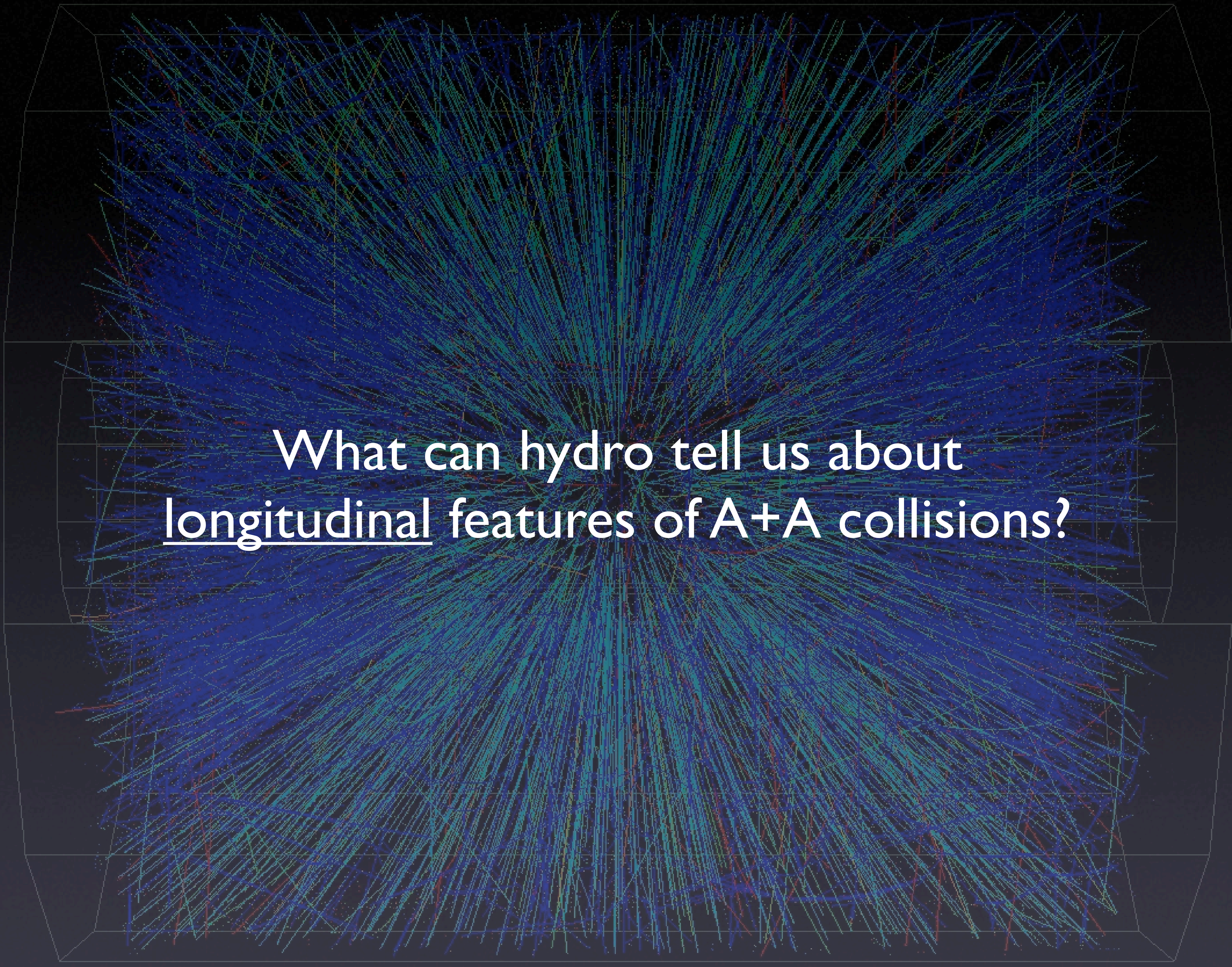


Smooth matter density



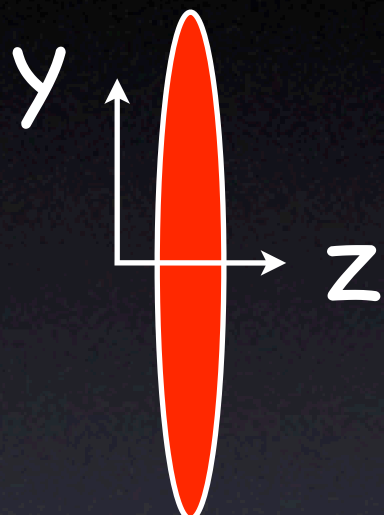
Clumpy bag of nucleons

If flow couples to the "clumpy" density, further evidence that it develops <u>extremely</u> early!

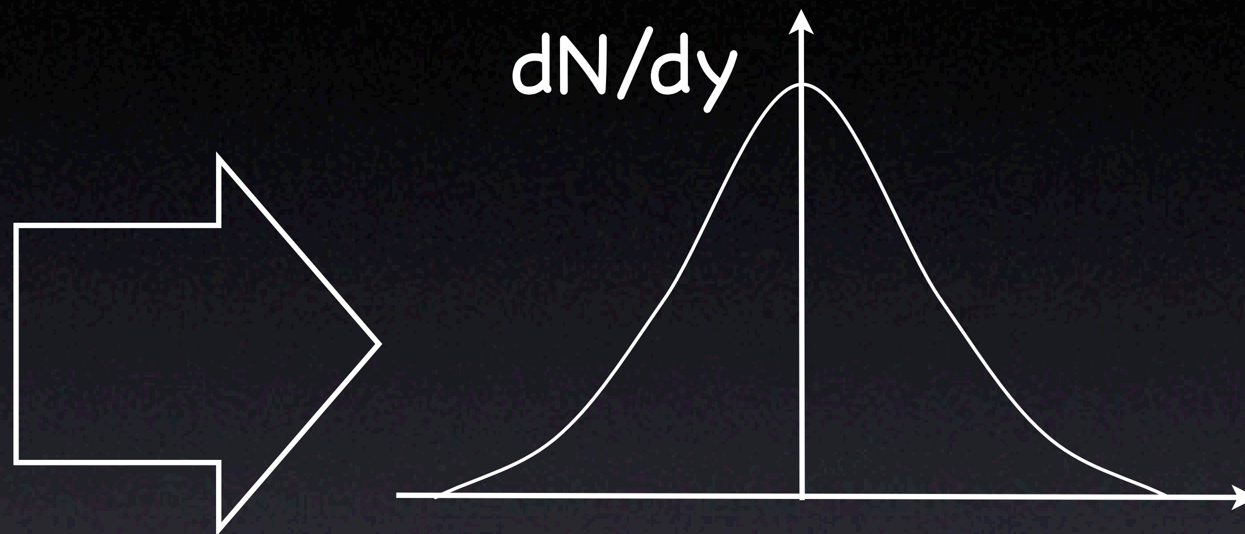


What can hydro tell us about longitudinal features of A+A collisions?

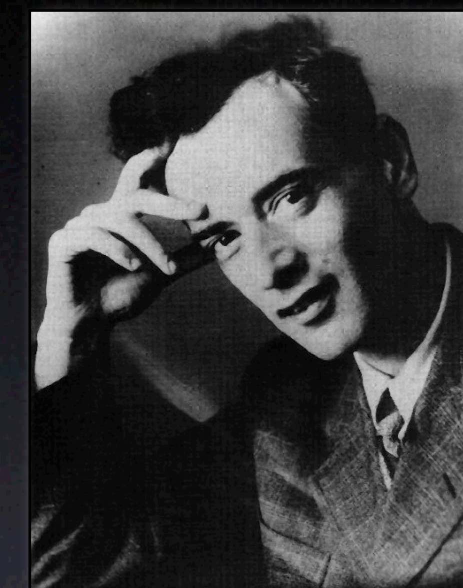
Longitudinal Flow



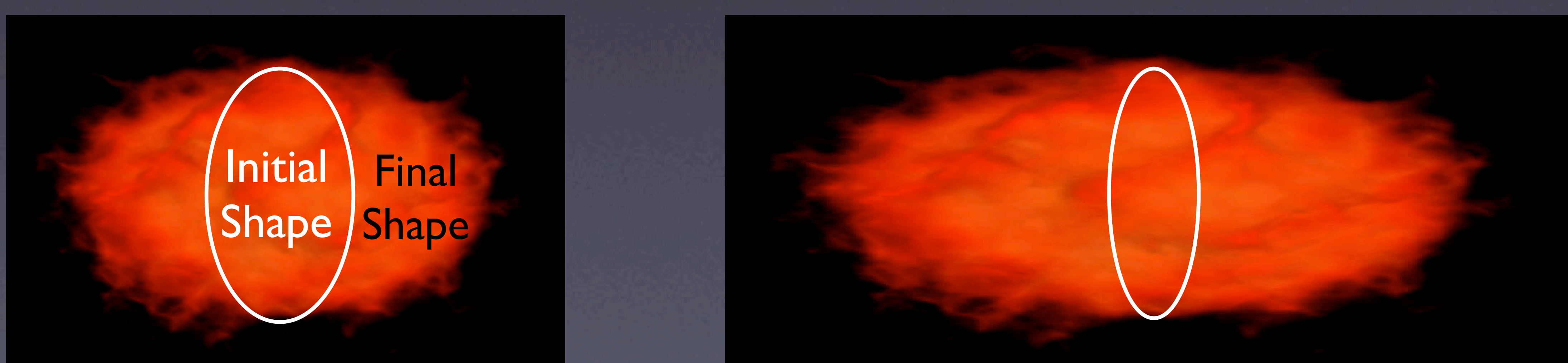
$$\Delta z \sim \frac{1}{\sqrt{s}}$$



$$\sigma_y^2 = \frac{1}{2}\log\left(\frac{s}{4M_P^2}\right)$$

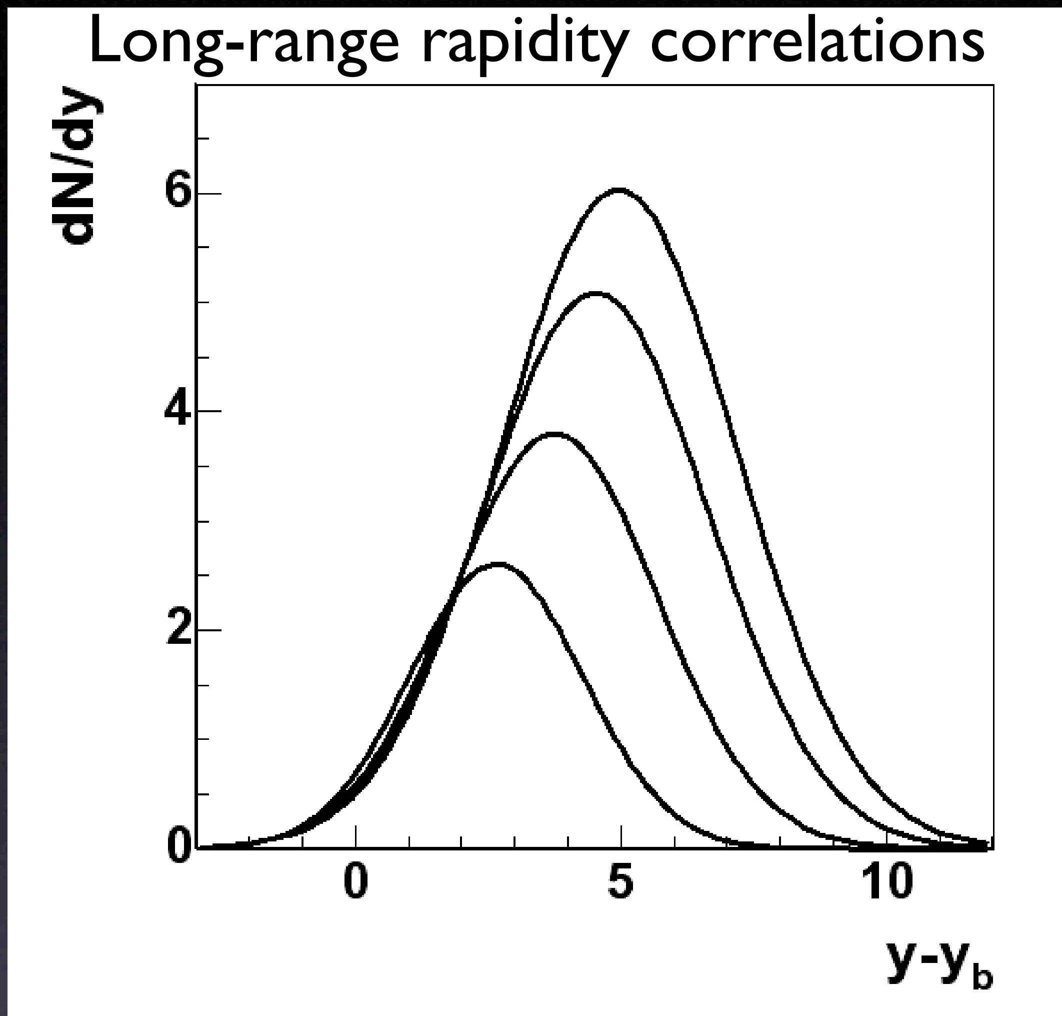


1955: Landau solves "Relativistic Hydrodynamics"

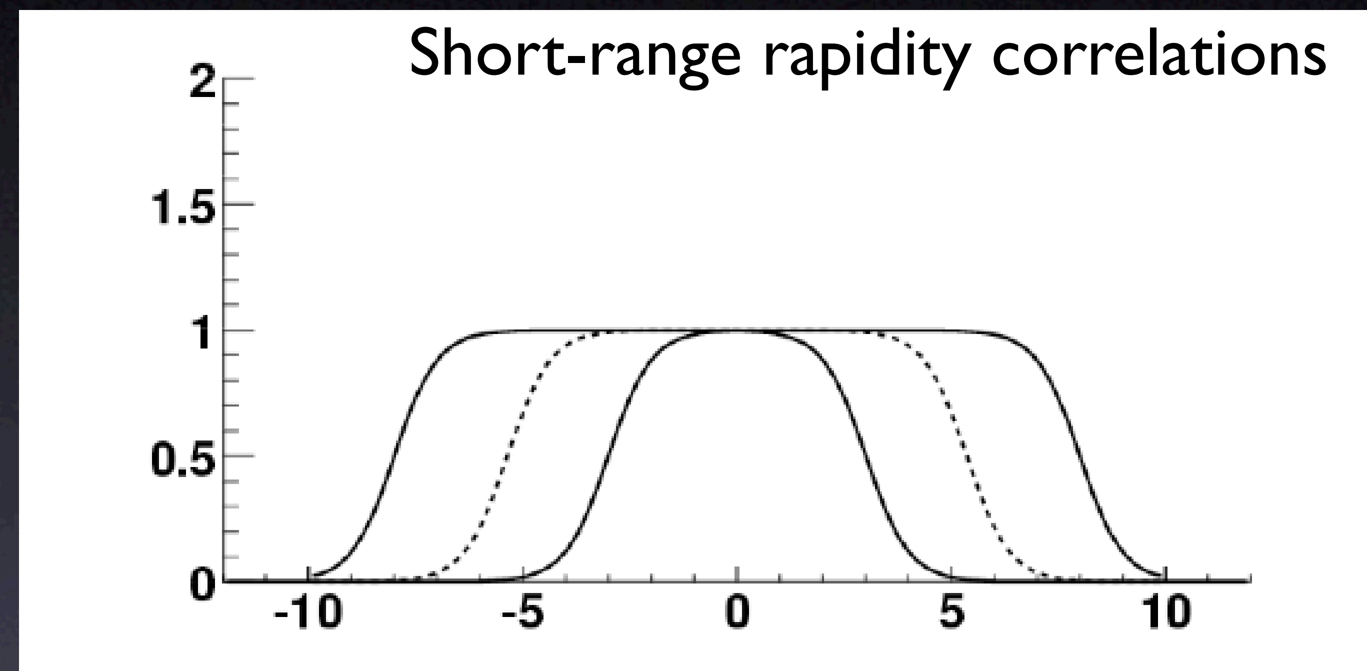


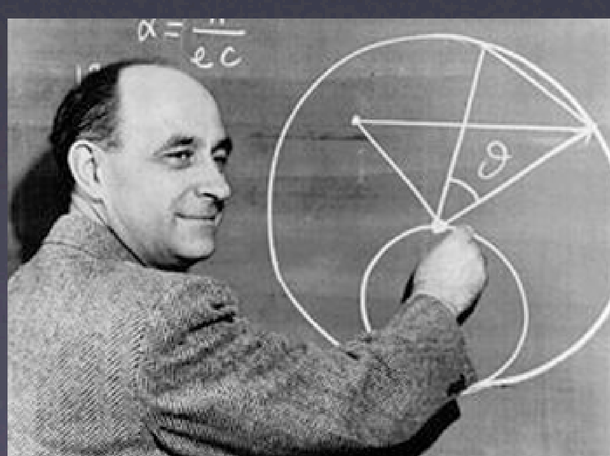
The more you squeeze it, the faster it explodes!

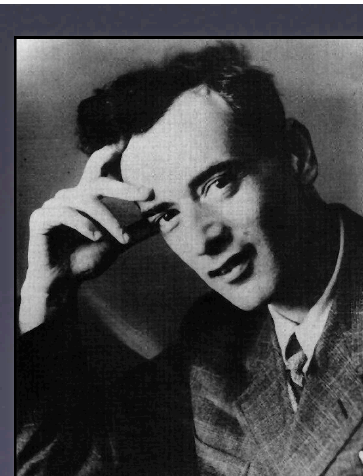
Boost Invariance



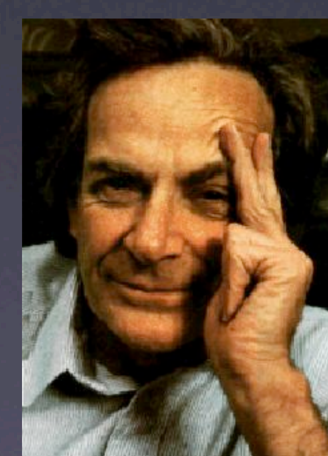
Two very different dynamical scenarios...





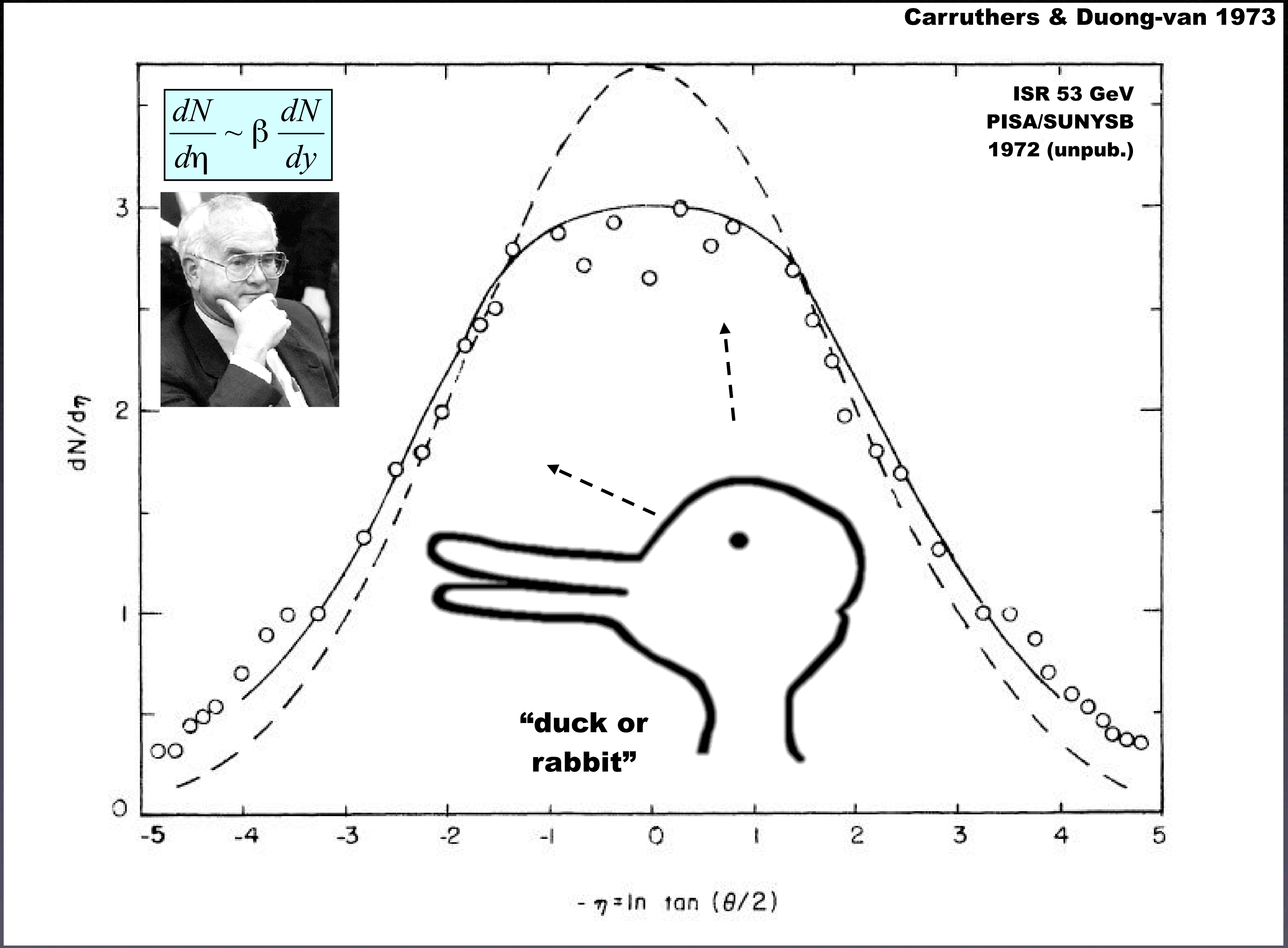


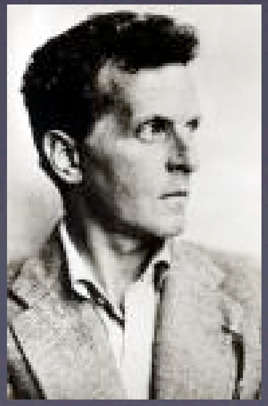
Fermi & Landau



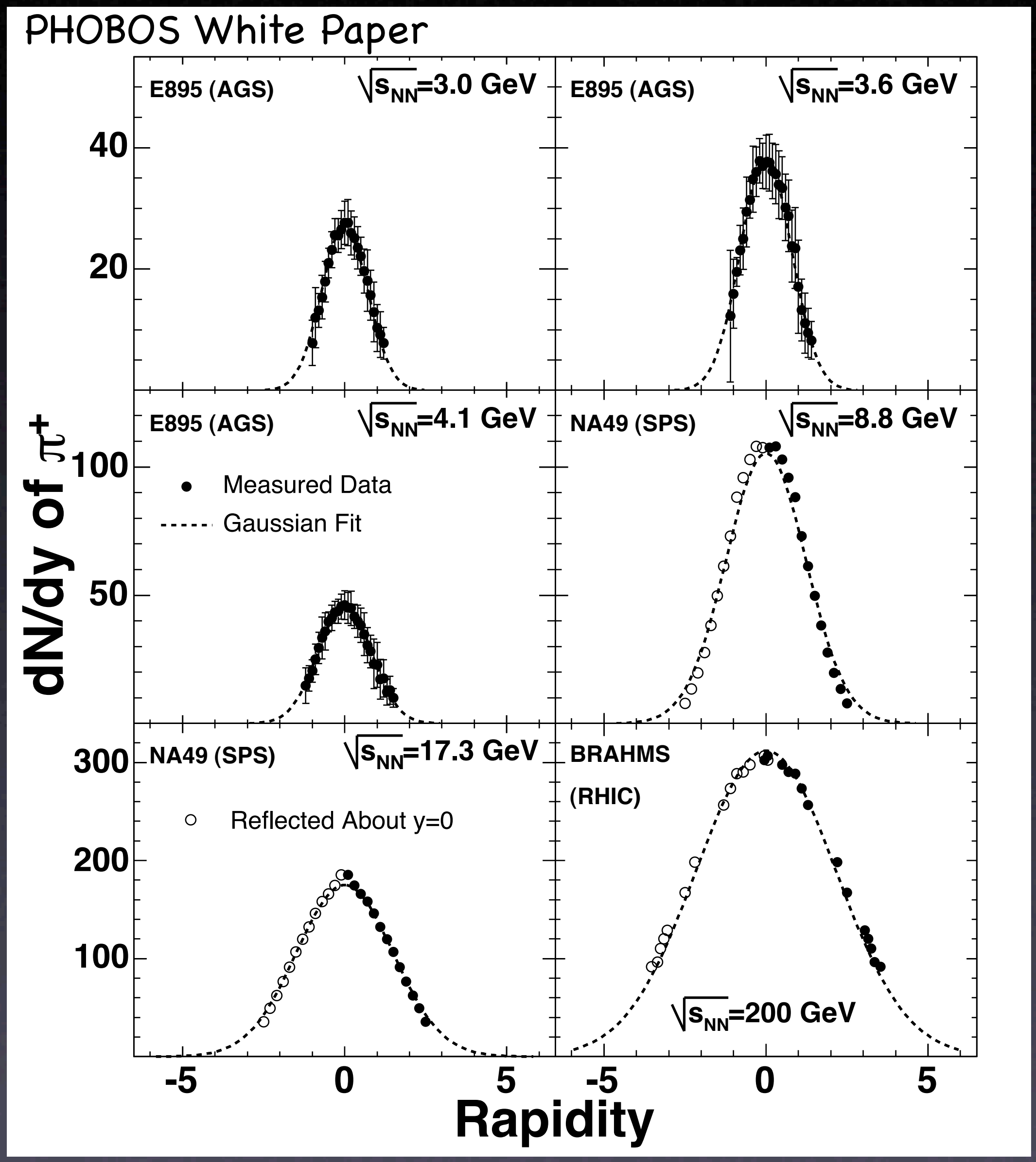
Feynman & Bjorken

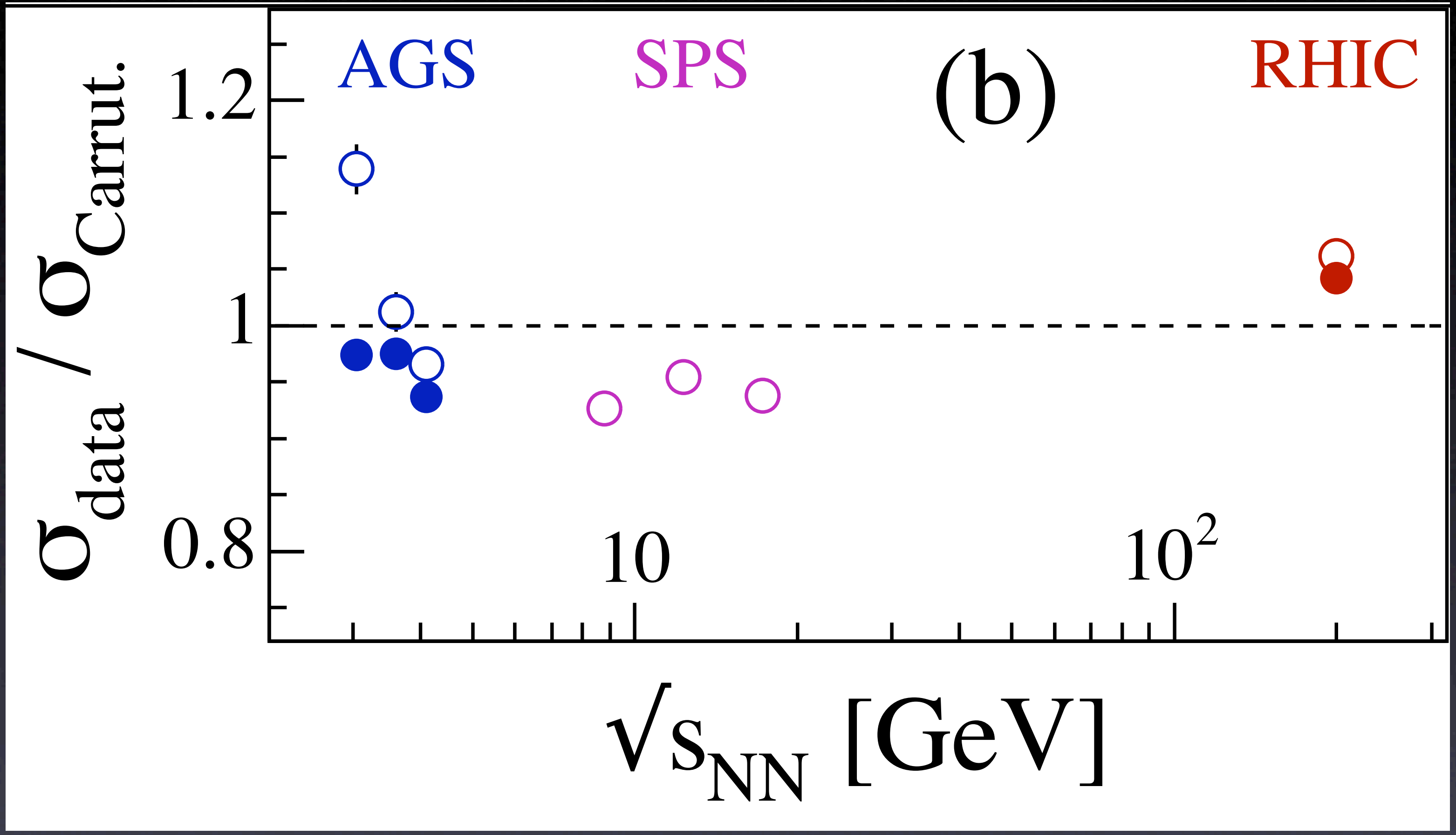
Eye of the Beholder?





Landau Model vs. Data





Landau's predictions from 1955 remain valid in 2005

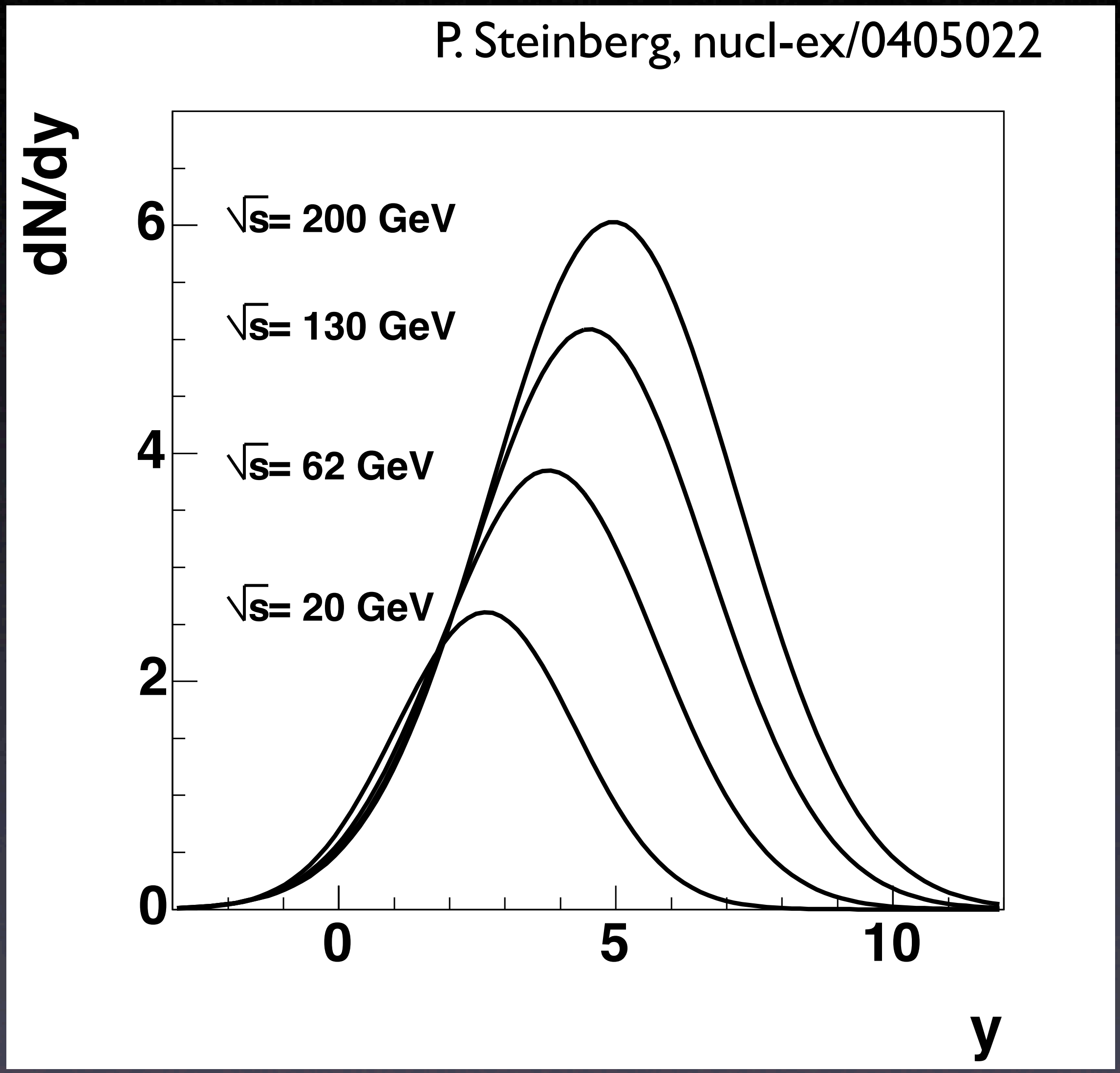
The longitudinal explosion in heavy ion collisions acts like a rapidly-thermalized fluid!

Longitudinal Scaling

$$\frac{dN}{dy} = K s^{1/4} \frac{1}{\sqrt{2\pi L}} \exp\left(-\frac{y^2}{2L}\right)$$

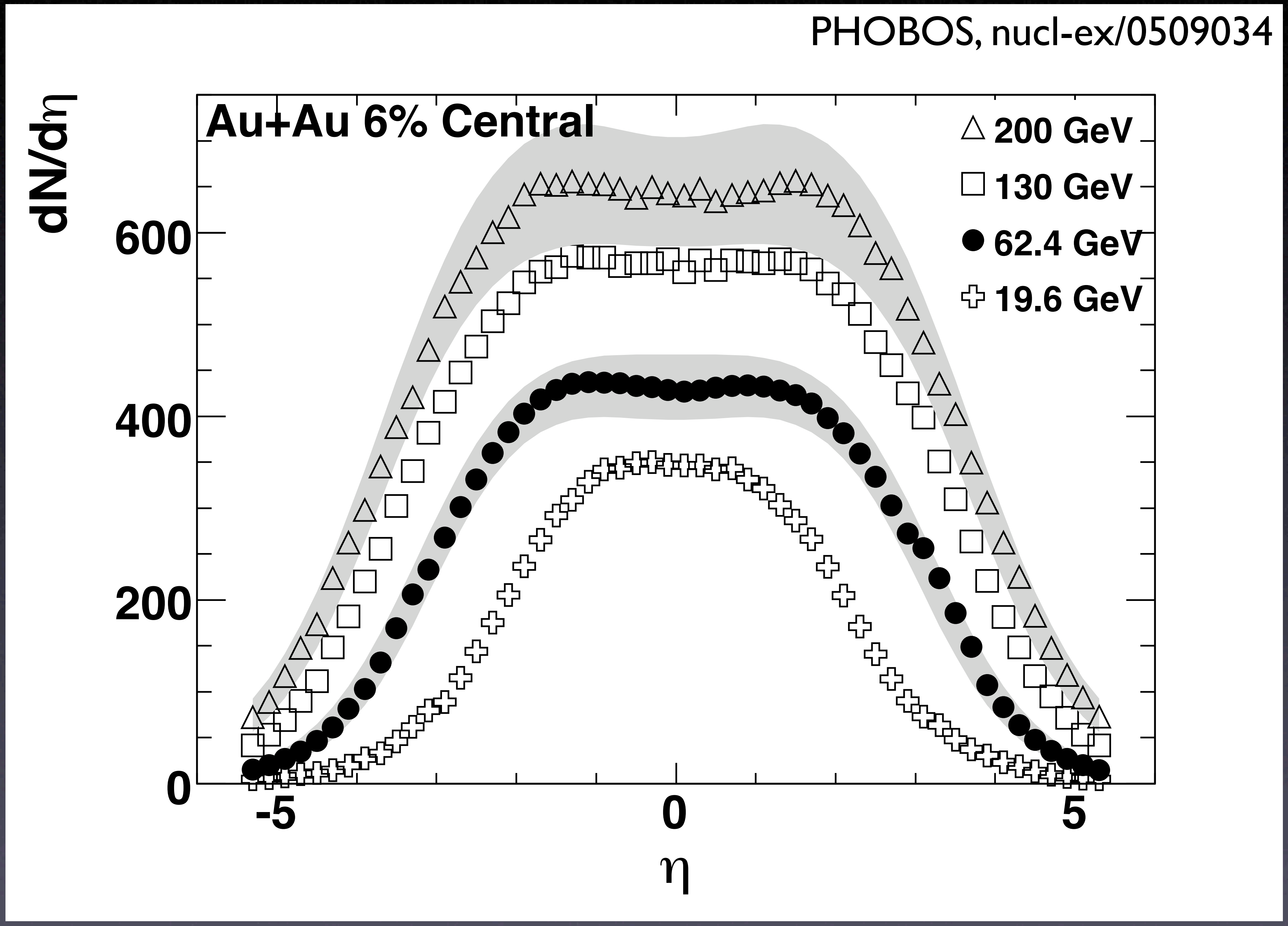
$$y' = y + y_{beam} = y + e^L$$

$$\frac{dN}{dy'} \sim \frac{1}{\sqrt{L}} \exp\left(-\frac{y'^2}{2L} - y'\right)$$

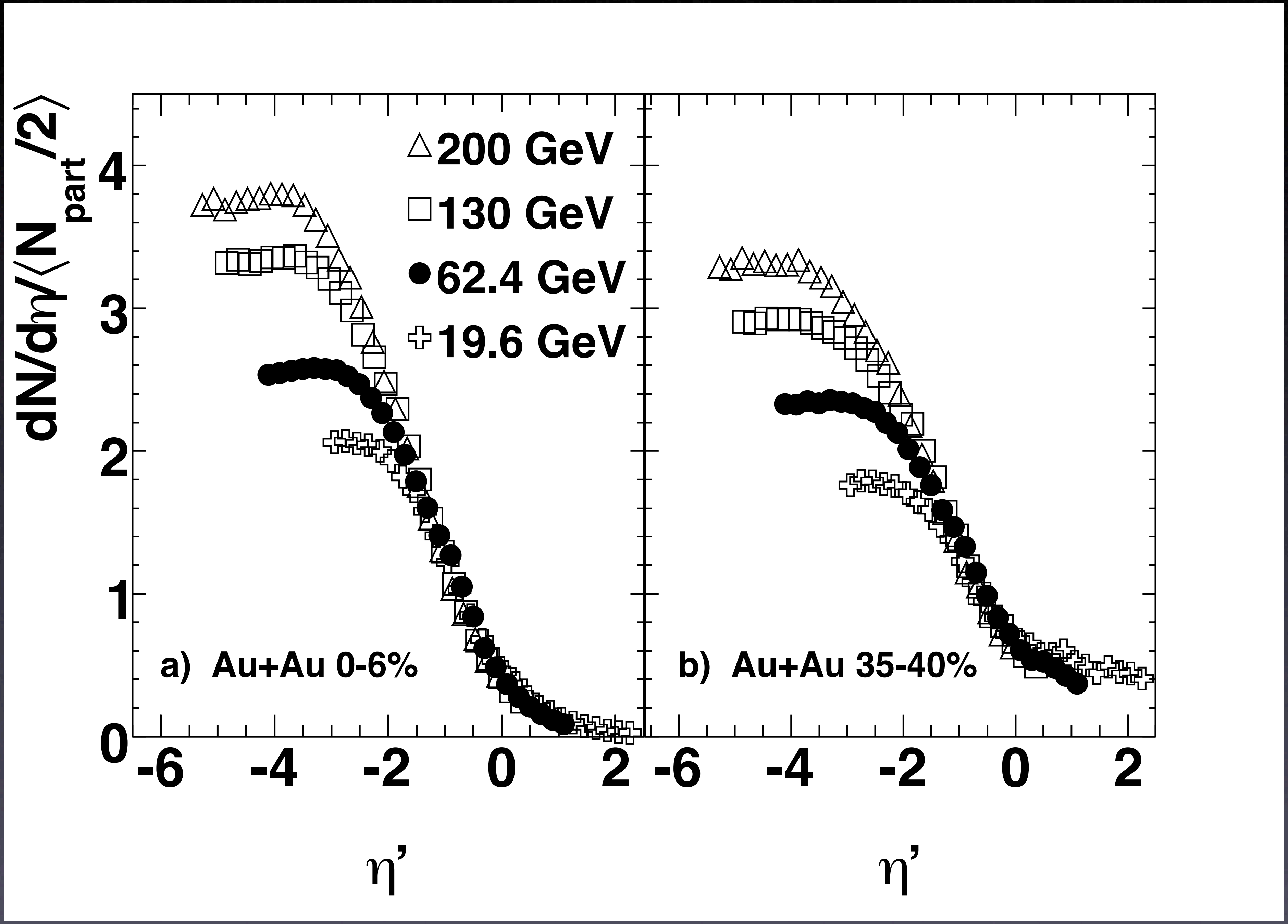


When observed in the rest frame of one of the projectiles ~invariance of particle yields!

4π Particle Densities

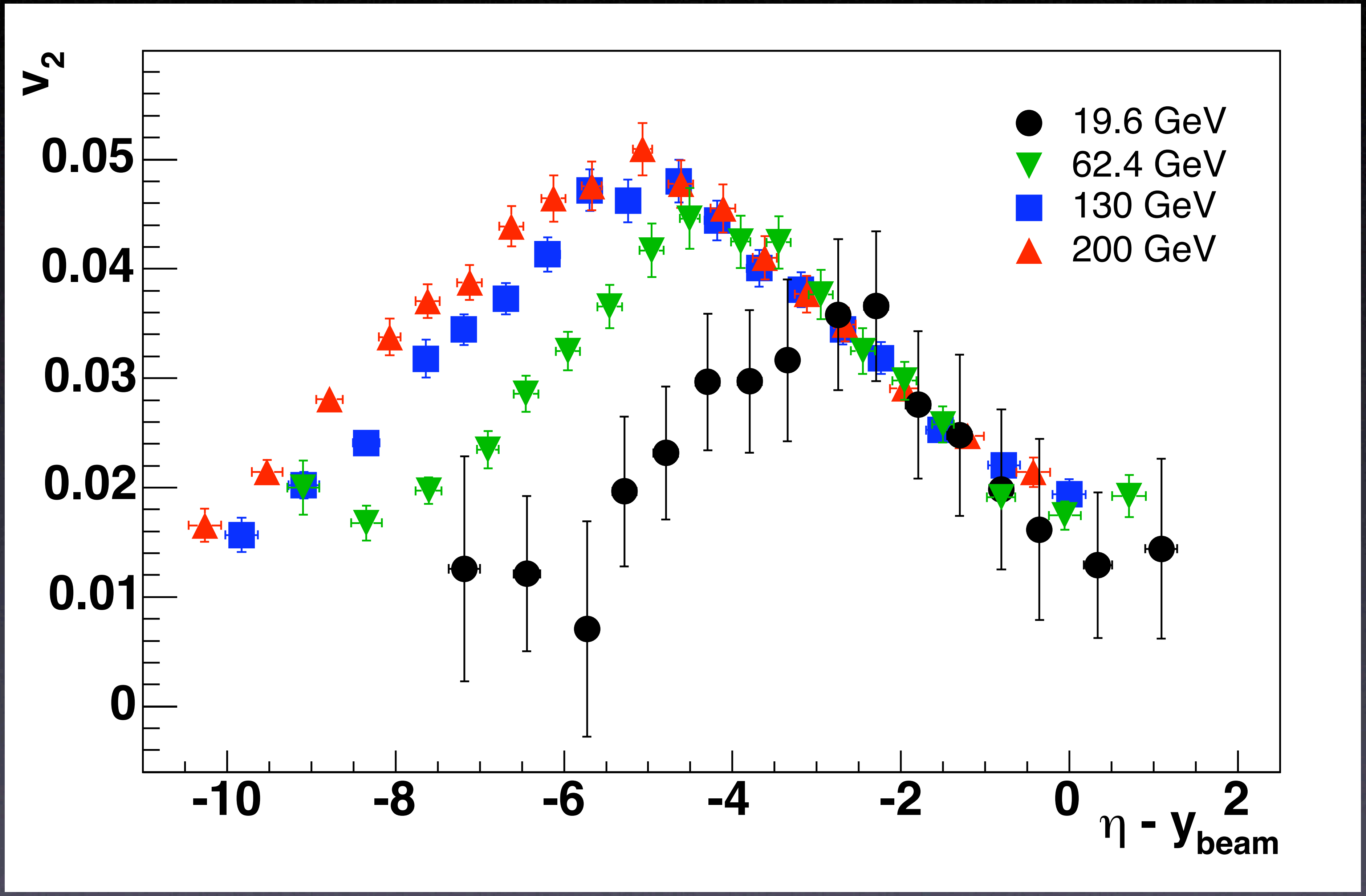


"Longitudinal Scaling"



Central events Peripheral events

Longitudinal Scaling

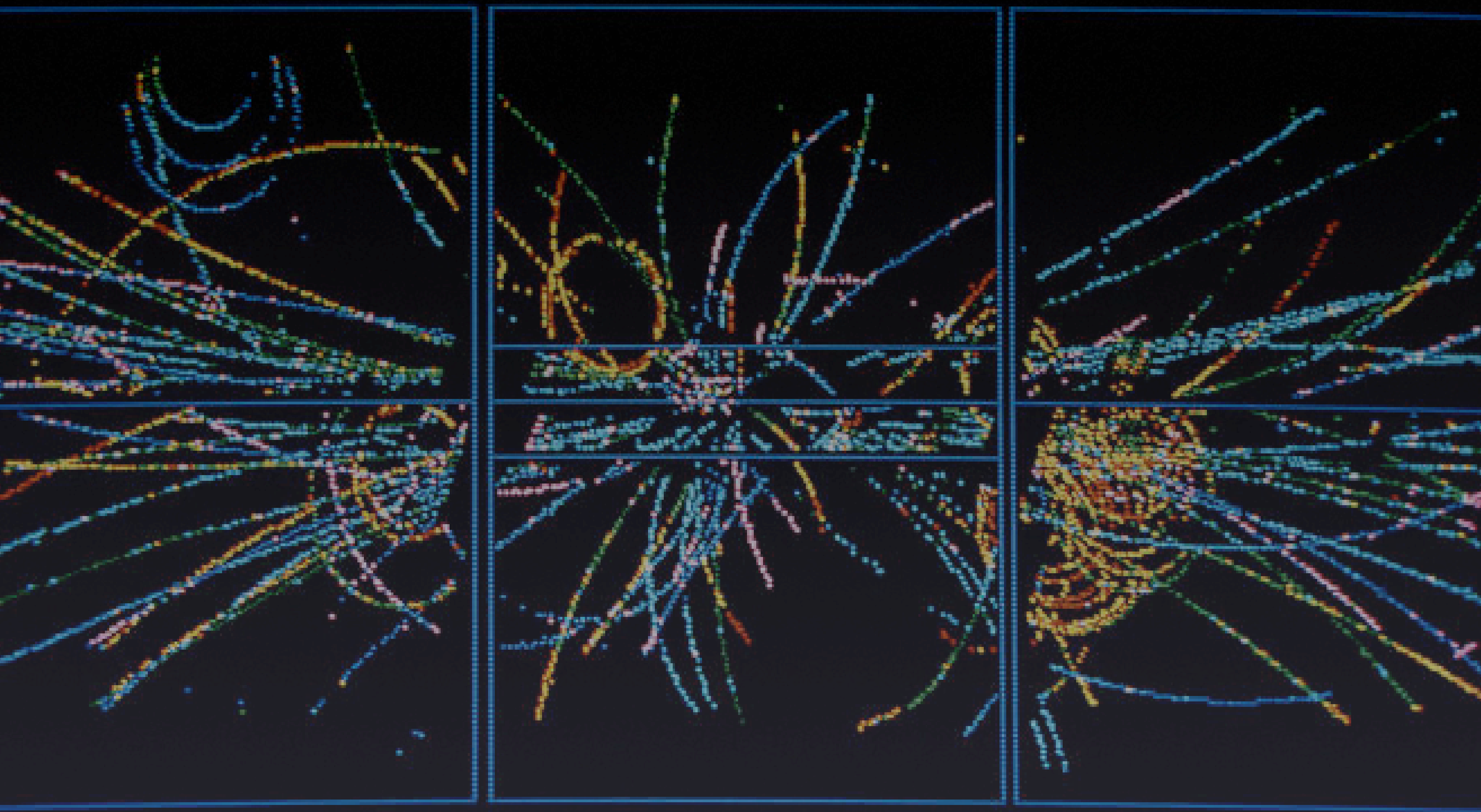


Does particle density control elliptic flow?
Remains to be seen if these data fit dN/dy/S scaling...

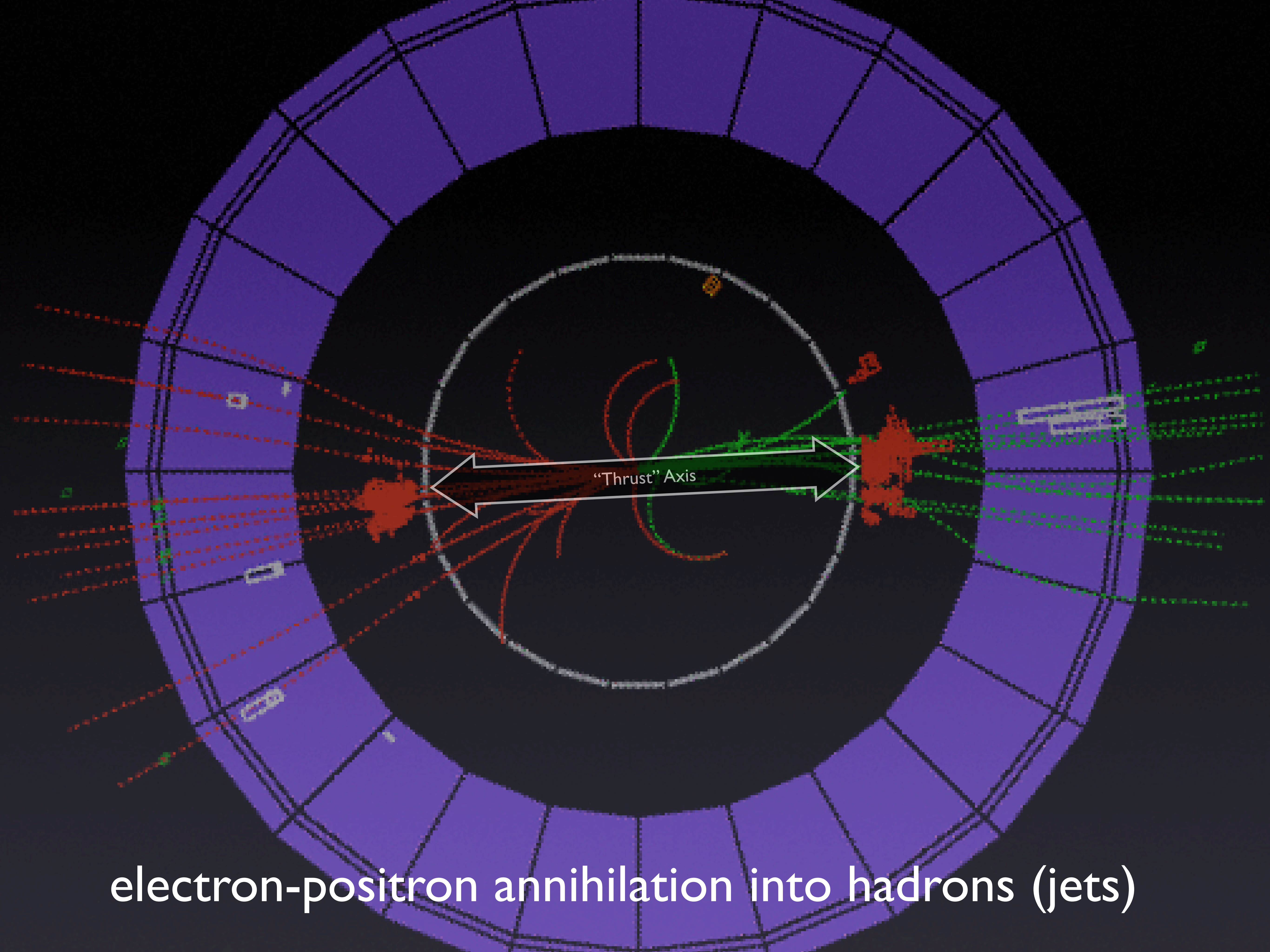
A+A Collisions appear
to achieve local thermal (and chemical) equilibrium

This is a profoundly small system.

How much smaller can it get and remain equilibrated?

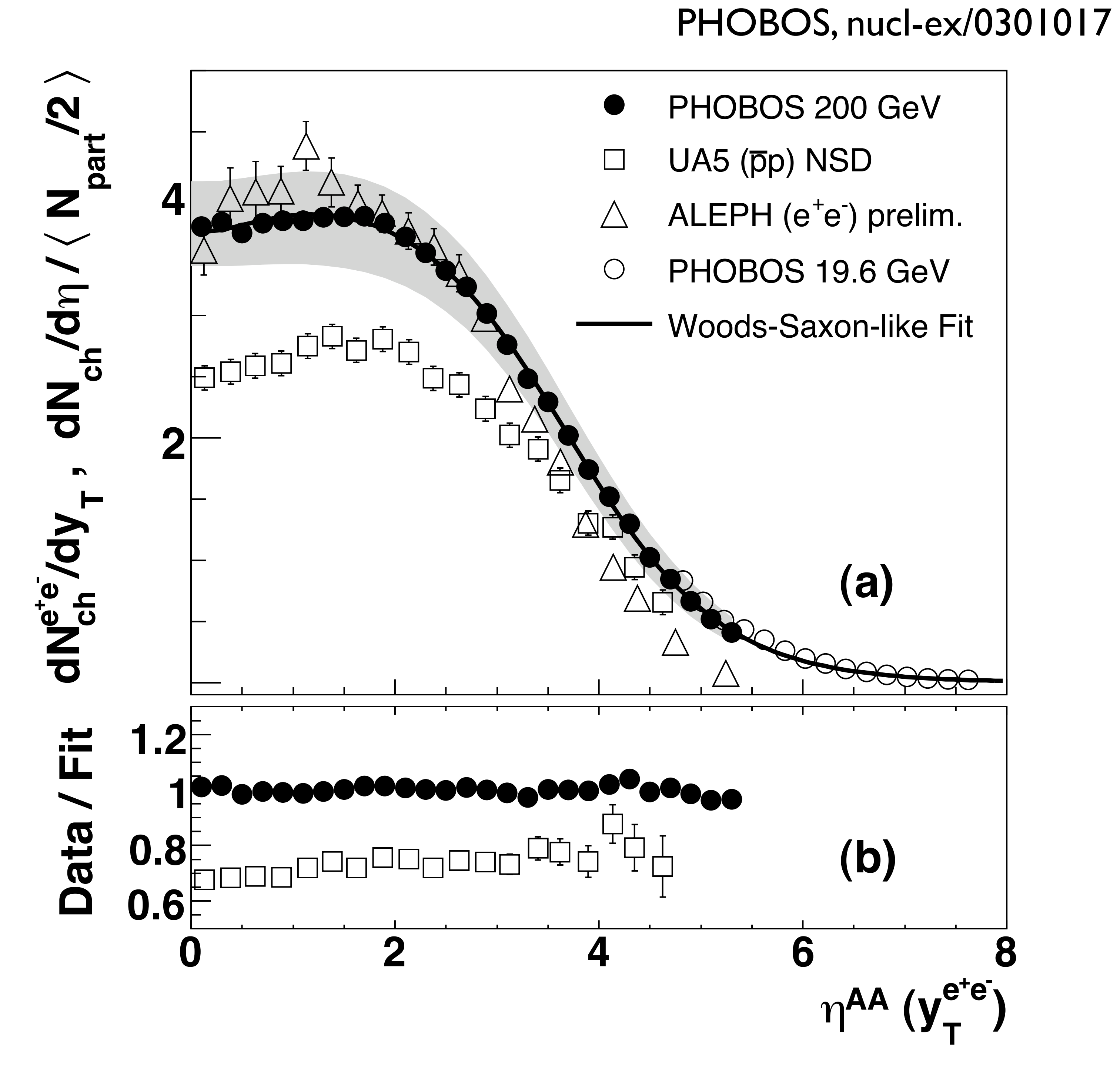


Proton-(anti) proton collisions?



electron-positron annihilation into hadrons (jets)

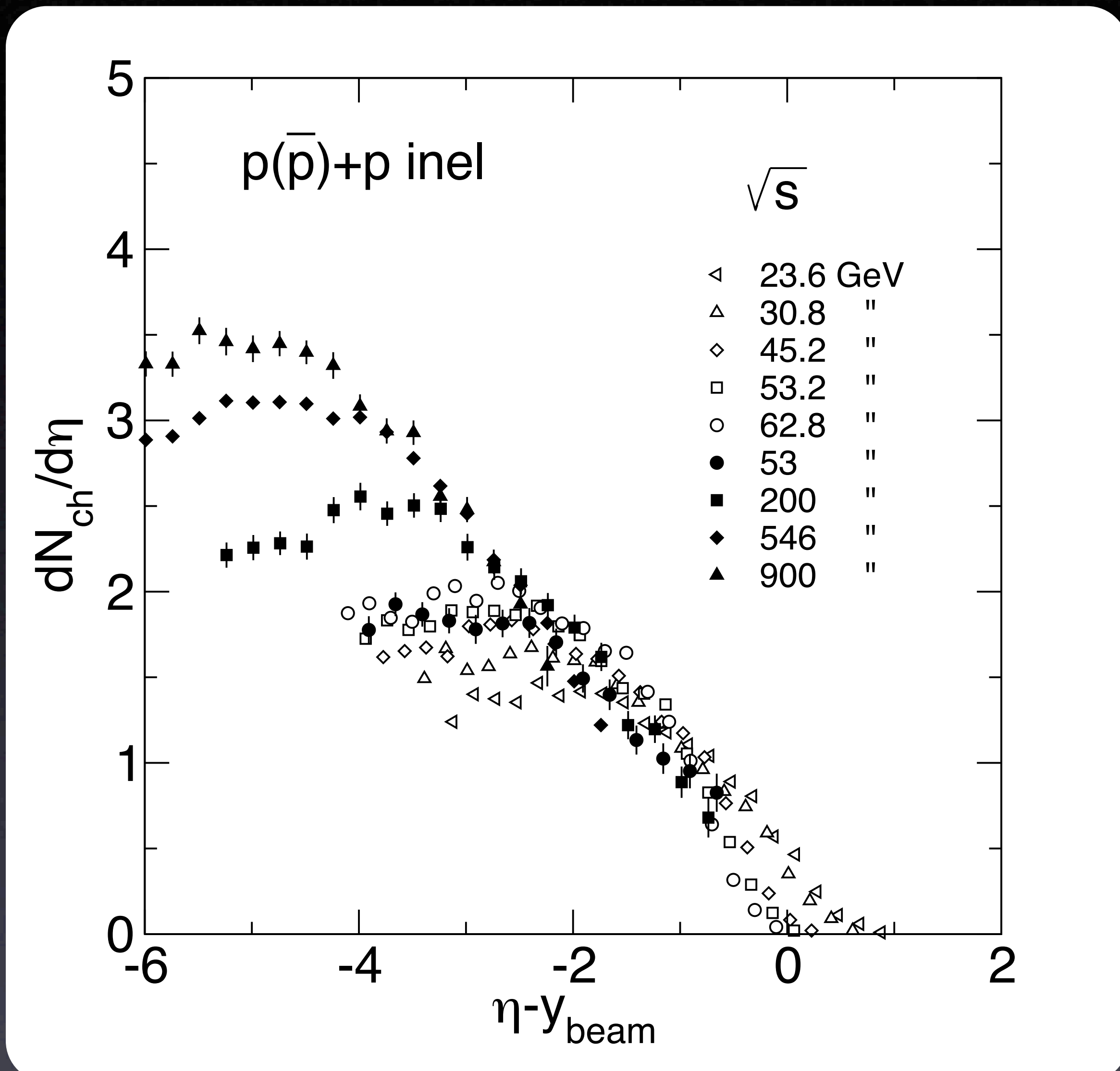
A+A vs. p+p (and e^+e^-)

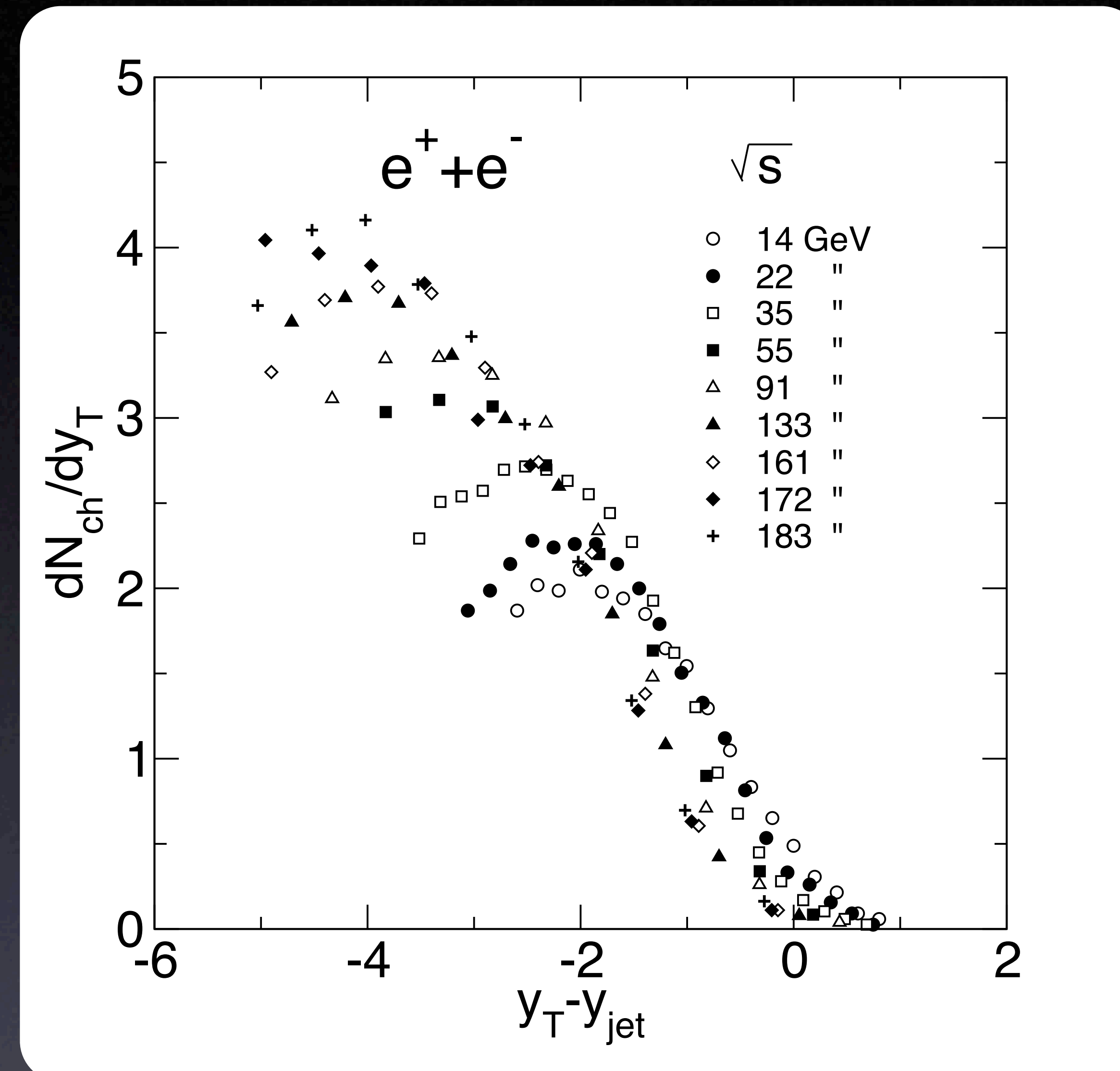


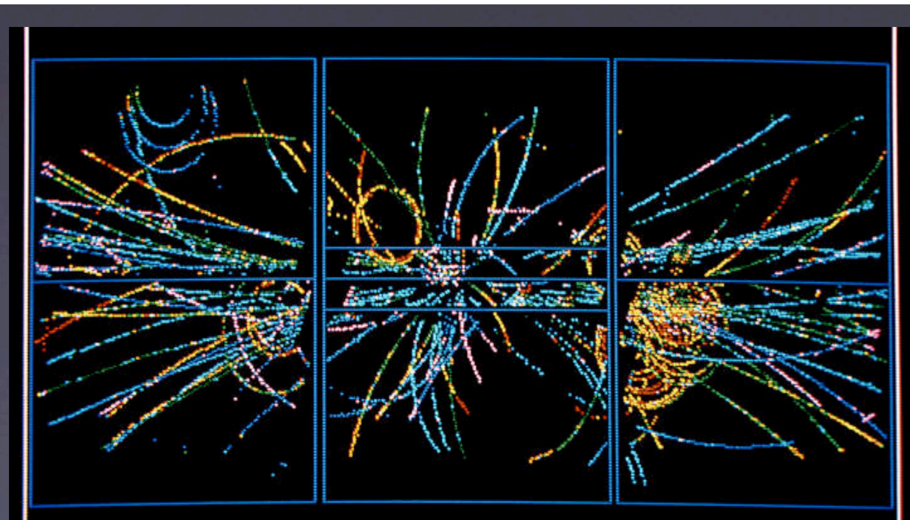
A+A ~
p+p x 4/3

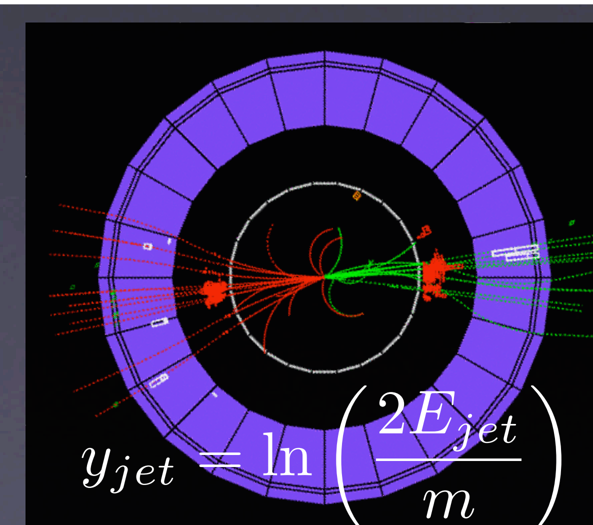
Similar angular distributions

Scaling in p+p and e$^+$e$^-$



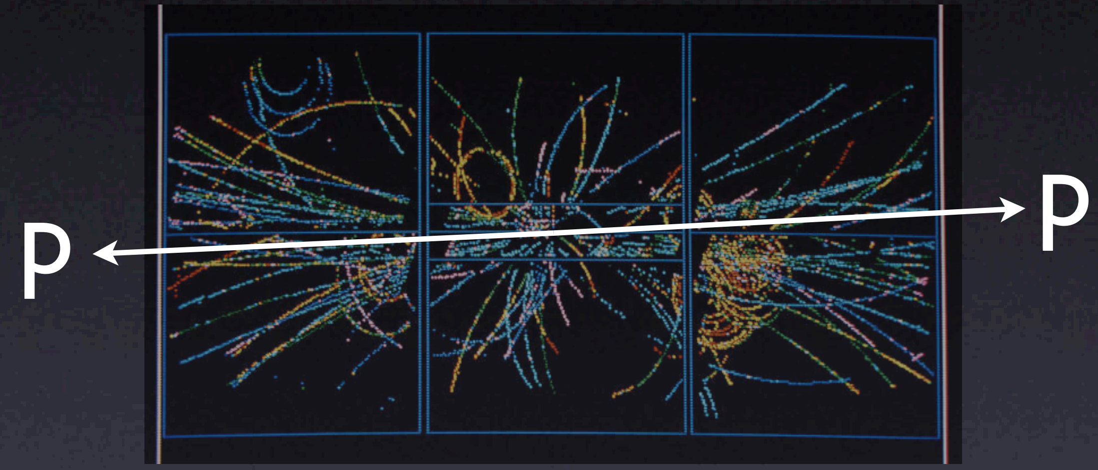






Leading Particle Effect

"leading" particles "keep" an arbitrary fraction of the initial energy

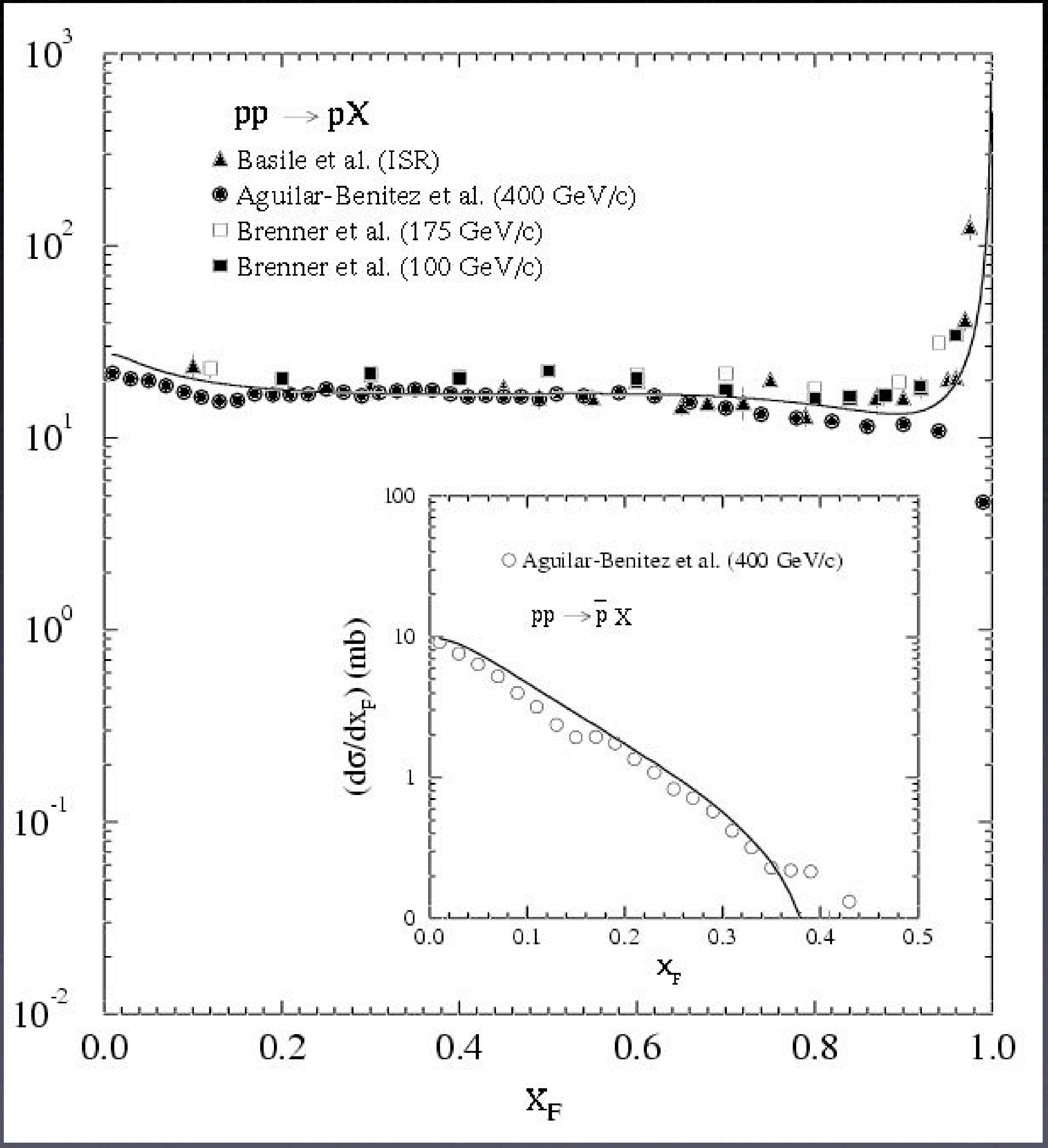


Flat probability distribution:

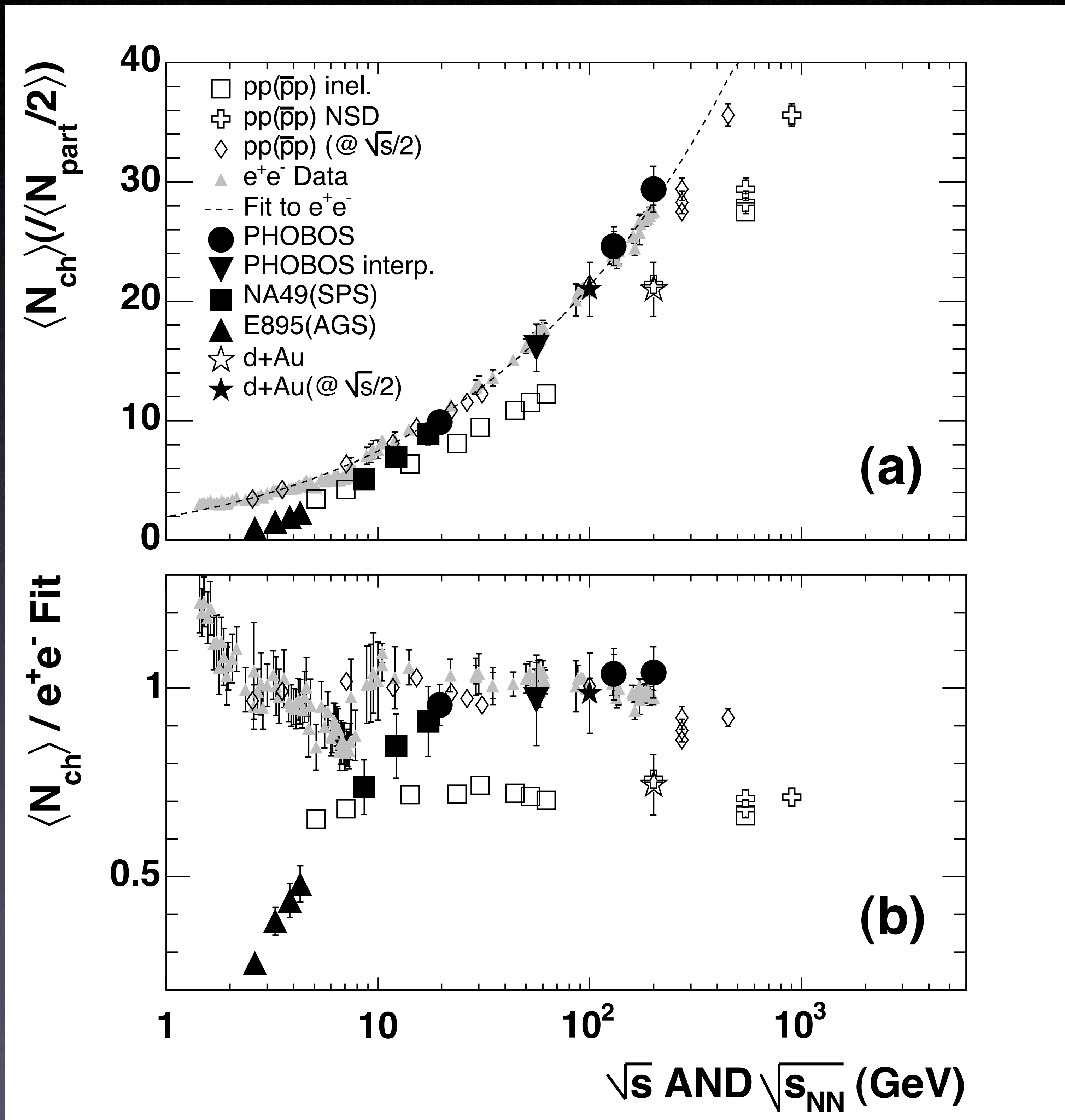
$$x_F = \frac{2p_z}{\sqrt{s}} \qquad \langle x_F \rangle \sim 1/2$$

$$\sqrt{s_{eff}} = \langle x_F \rangle \sqrt{s} = \frac{\sqrt{s}}{2}$$

"effective energy"
(a la Basile et al)



Total Multiplicity

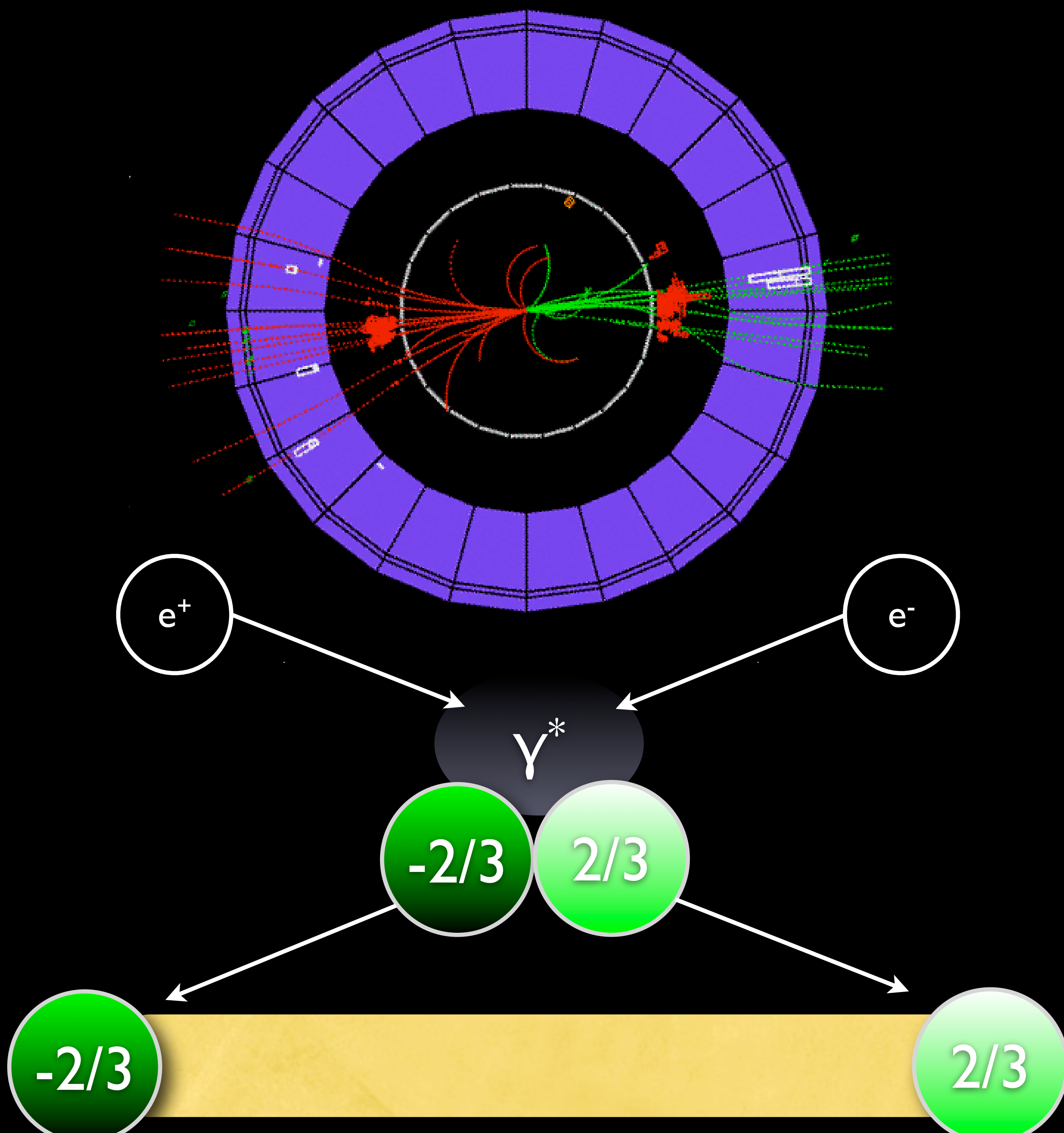


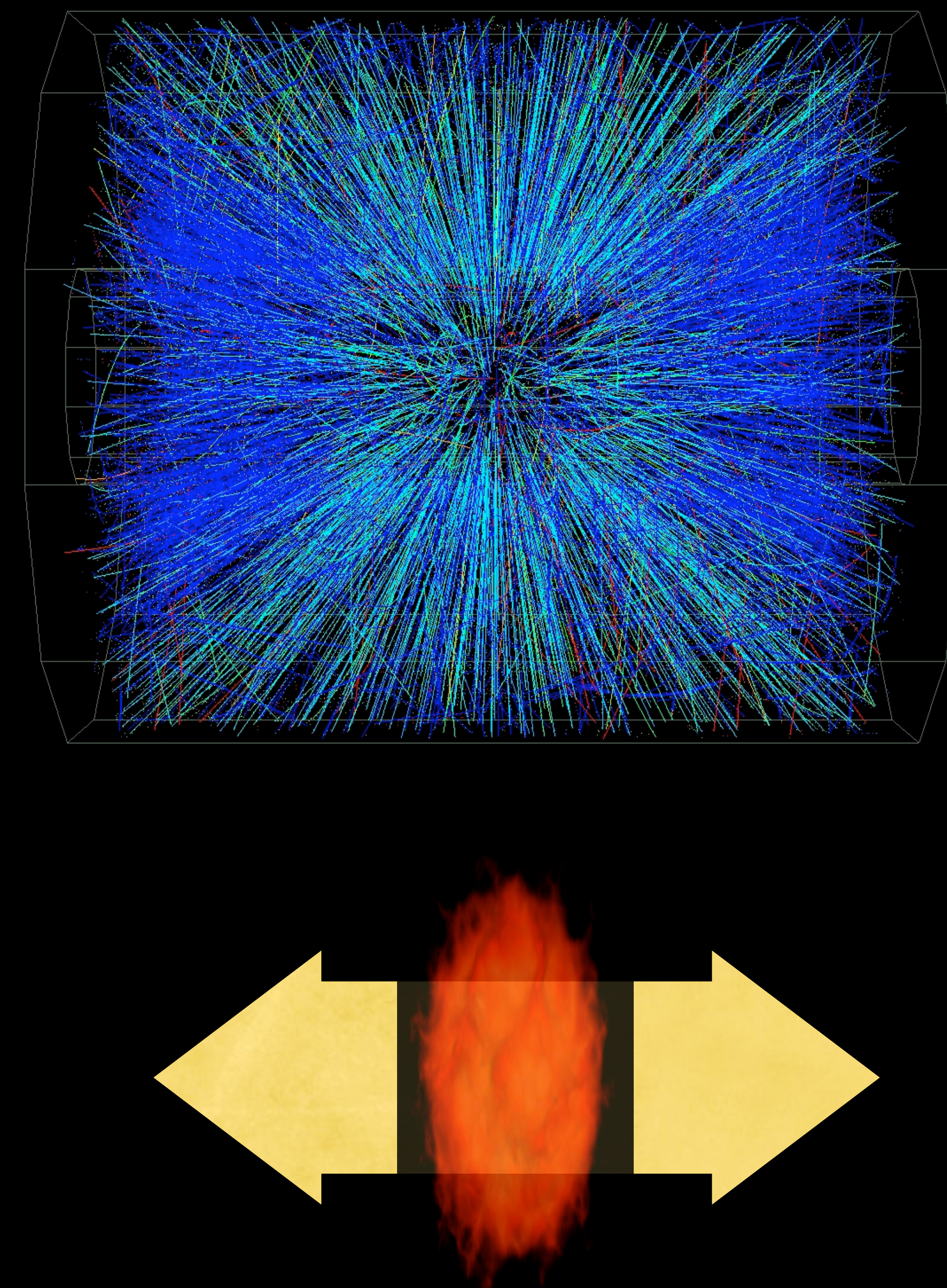
Total multiplicity vs. energy for A+A, p+p, e+e- (d+Au)

Divided by fit to e^+e^- (based on pQCD)

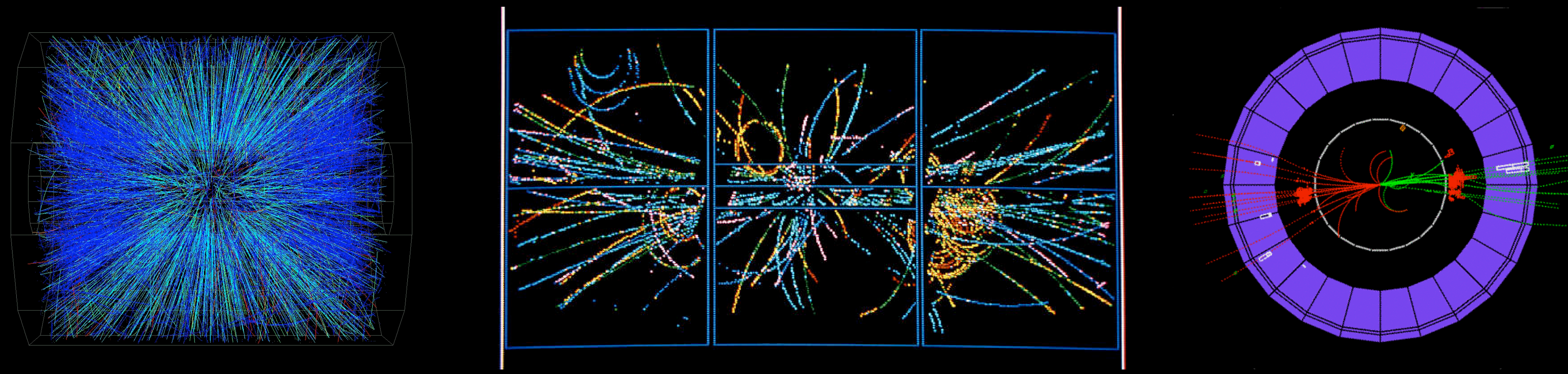
$$n_{ch} \propto \alpha_s^A \exp(B/\sqrt{\alpha_s})$$

e^+e^- vs. A+A



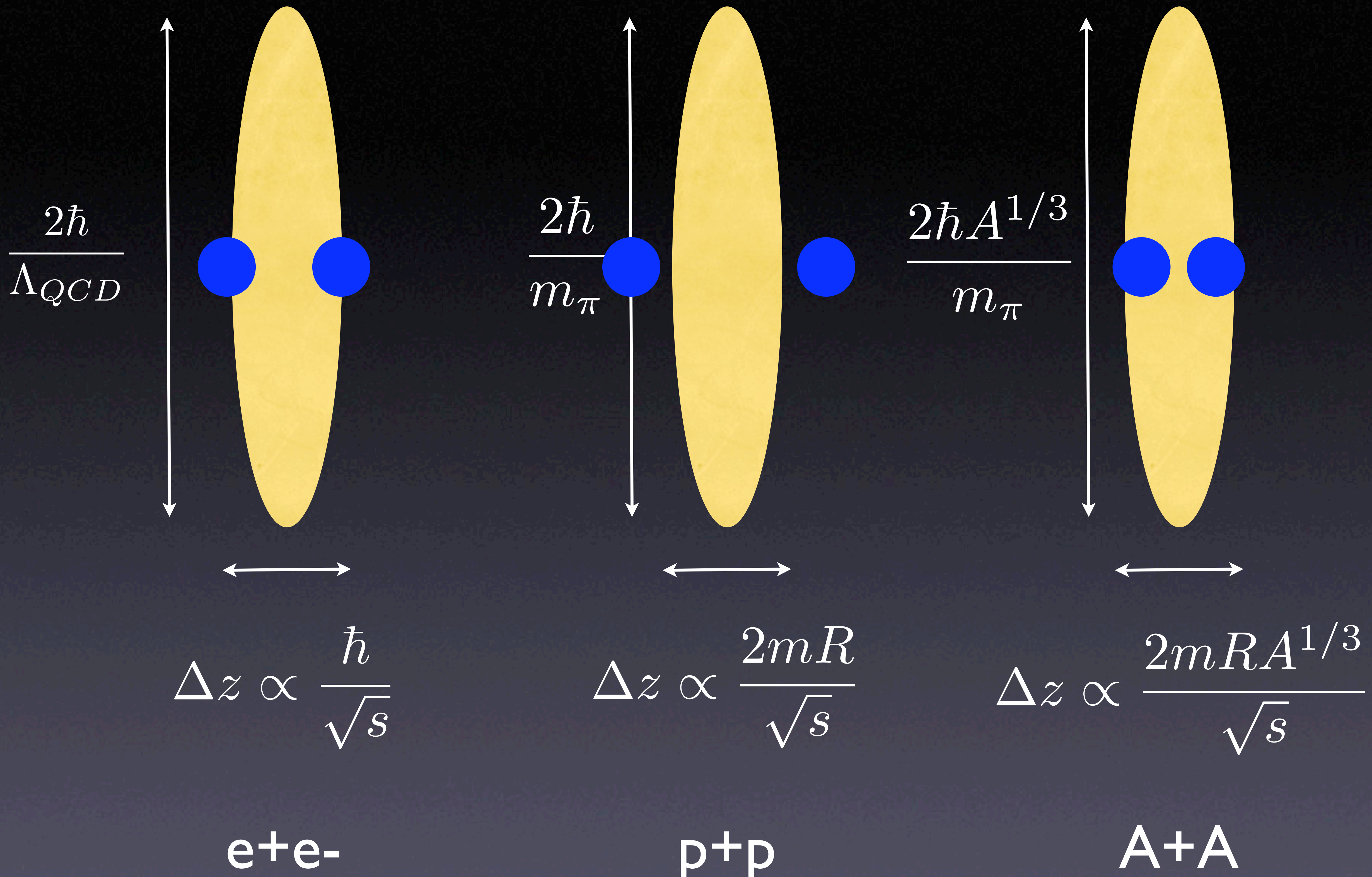


Similar features after dividing by $N_{part}/2$



What could be the same in these systems?

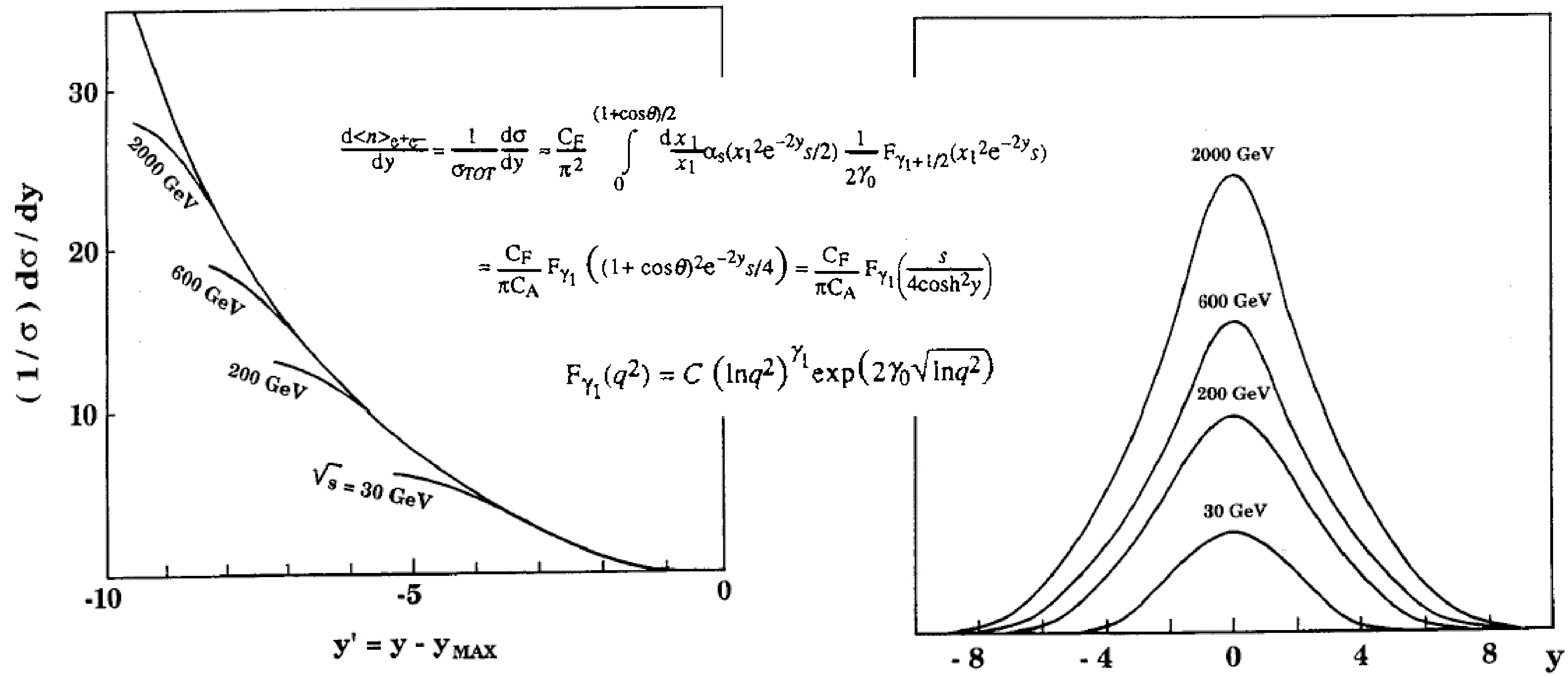
What if we treat <u>all</u> strongly interacting systems in the hydrodynamic (and thus statistical/thermal) paradigm, and with <u>Landau</u> initial conditions



Similar geometries <u>and</u> energy densities (& net baryons?)

pQCD vs. Landau

K. Tesima, Z. Phys. C (1989)



$$\frac{d\langle n\rangle_{e^+e^-}}{dy} = \frac{1}{\sigma_{TOT}}\frac{d\sigma}{dy} \approx \frac{C_F}{\pi^2}\int_0^{(1+\cos\theta)/2}\frac{dx_1}{x_1}\alpha_s(x_1{}^2 e^{-2y}s/2)\,\frac{1}{2\gamma_0}\,F_{\gamma_1+1/2}(x_1{}^2 e^{-2y}s)$$

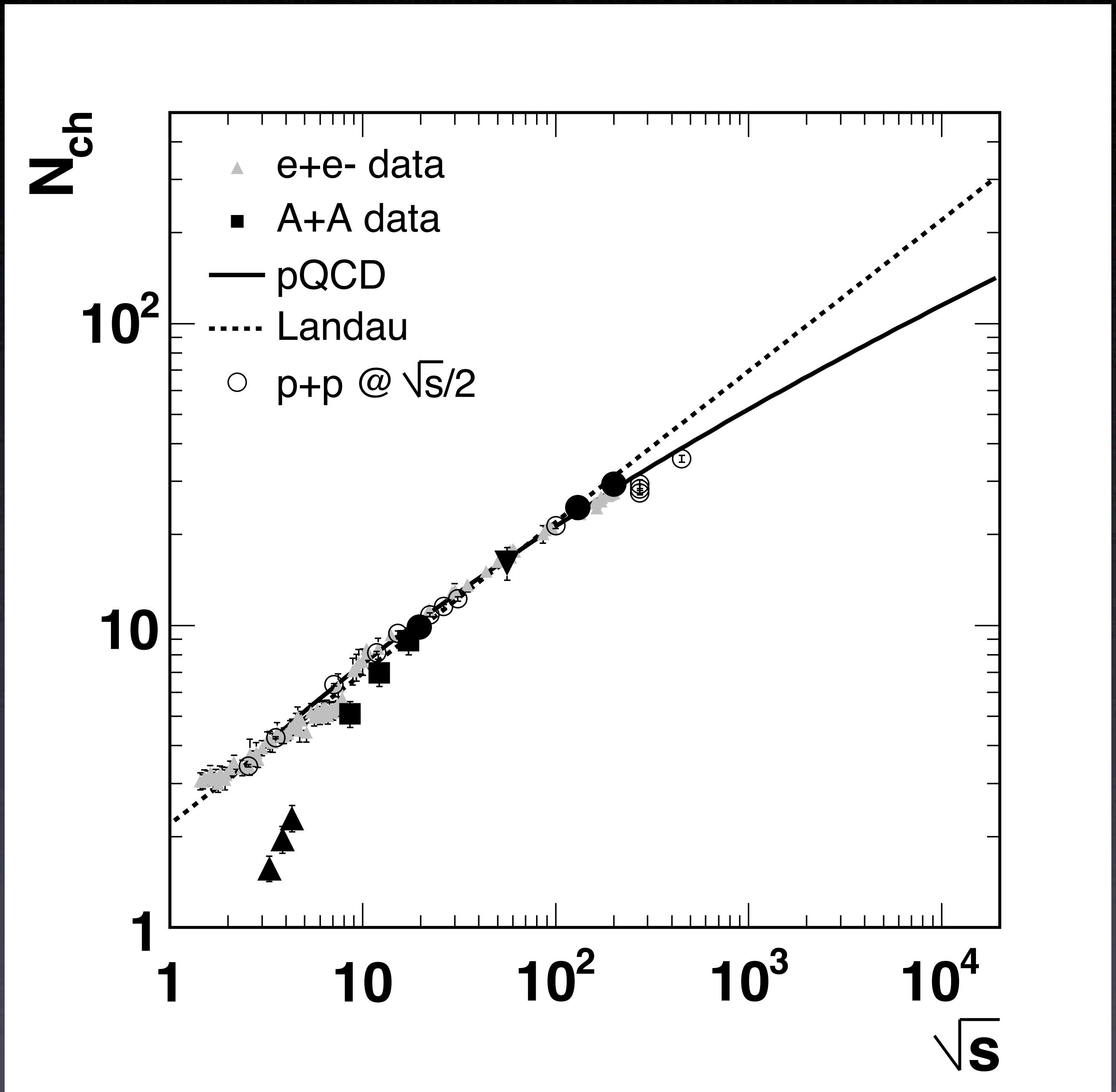
$$\approx \frac{C_F}{\pi C_A}F_{\gamma_1}\left((1+\cos\theta)^2 e^{-2y}s/4\right) = \frac{C_F}{\pi C_A}F_{\gamma_1}\left(\frac{s}{4\cosh^2 y}\right)$$

$$F_{\gamma_1}(q^2) = C\,(\ln q^2)^{\gamma_1}\exp\left(2\gamma_0\sqrt{\ln q^2}\right)$$

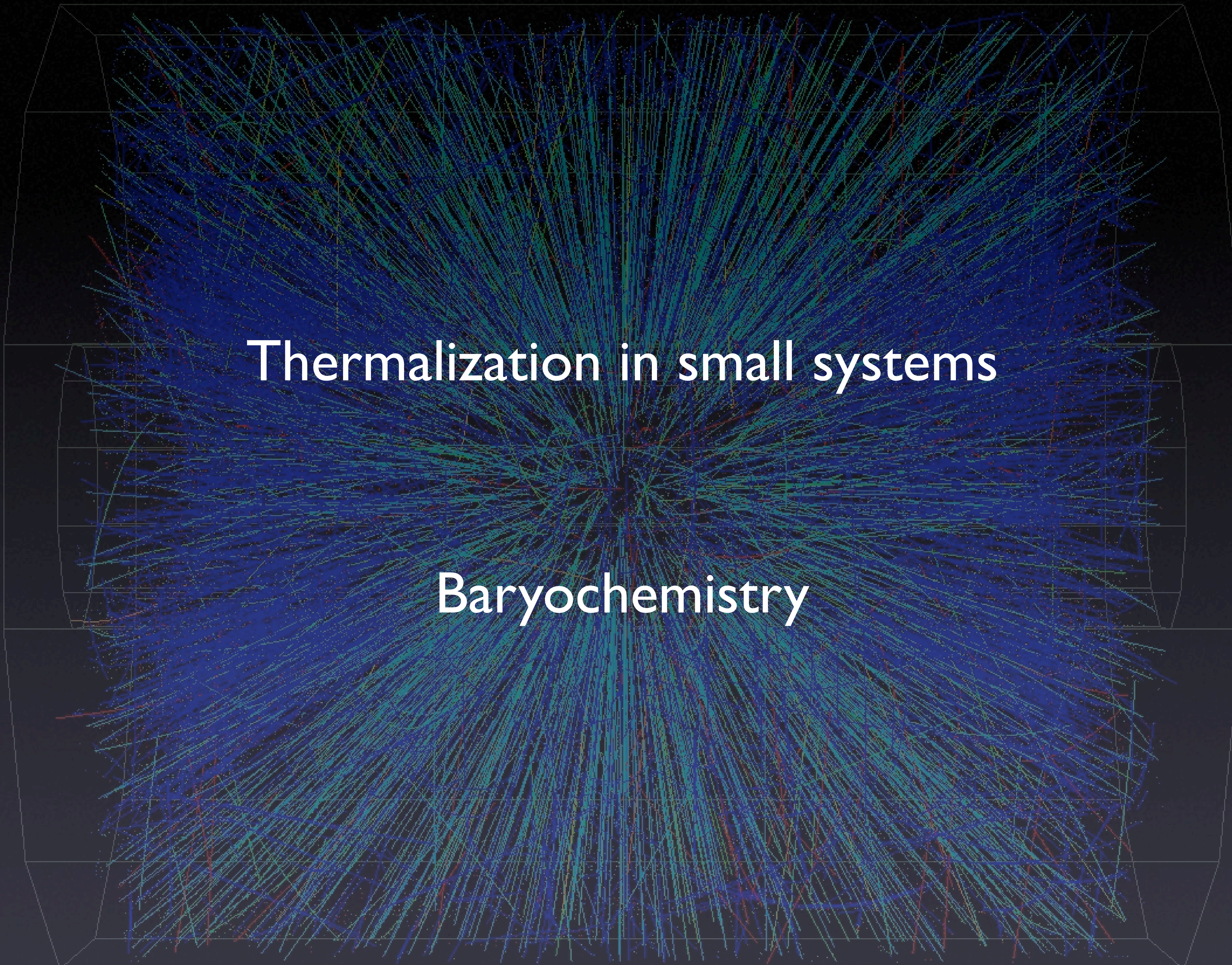
MLLA pQCD shows "limiting fragmentation" & $\sigma_y \propto \sqrt{log(s)}$

Why would resummed QCD give similar features?

pQCD vs. Landau



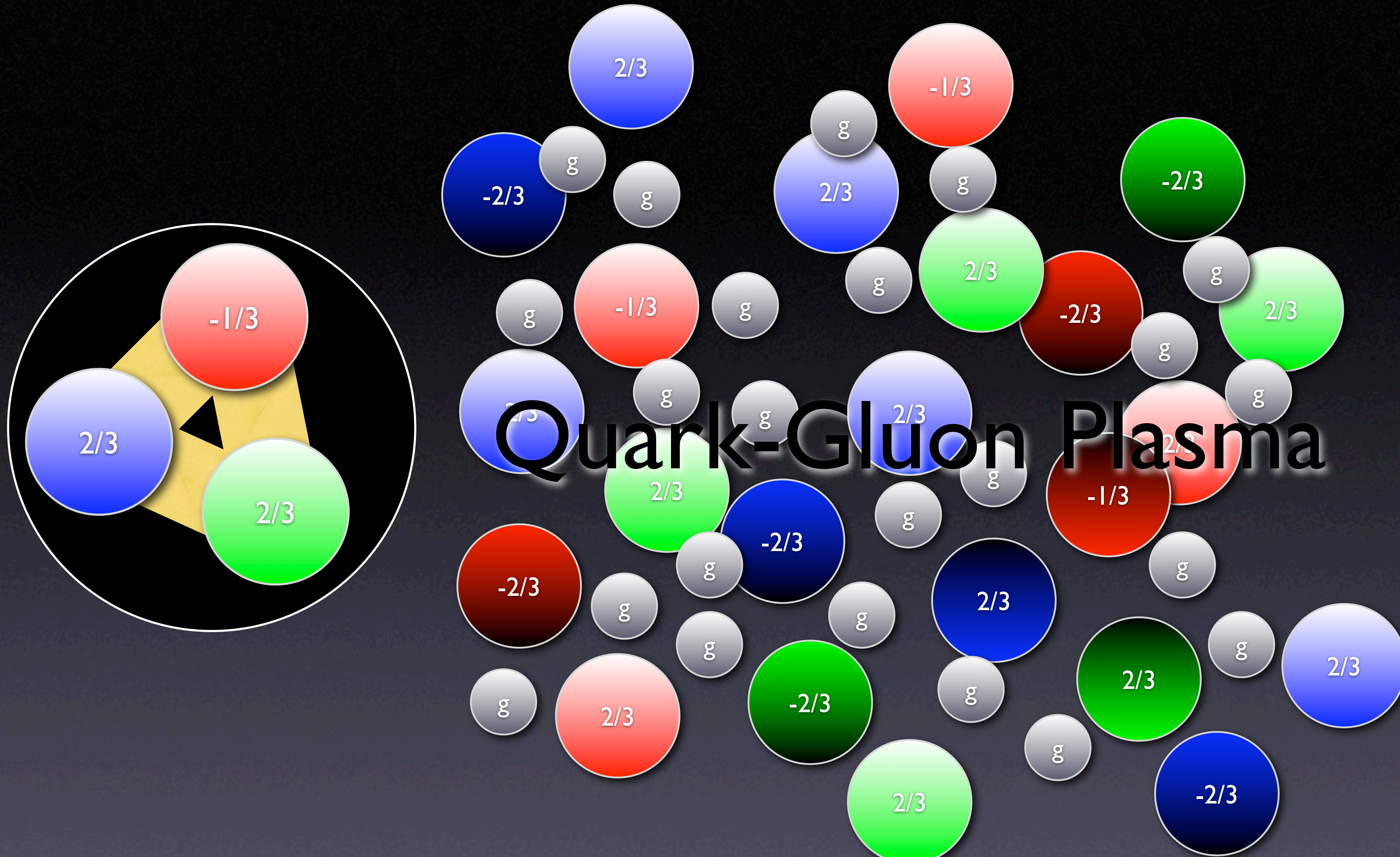
It has long been noted that pQCD & Landau multiplicity formulae give similar answers over a range of energies (LHC will be a crucial test in p+p and A+A!)



Thermalization in small systems

Baryochemistry

Quark-Gluon Plasma



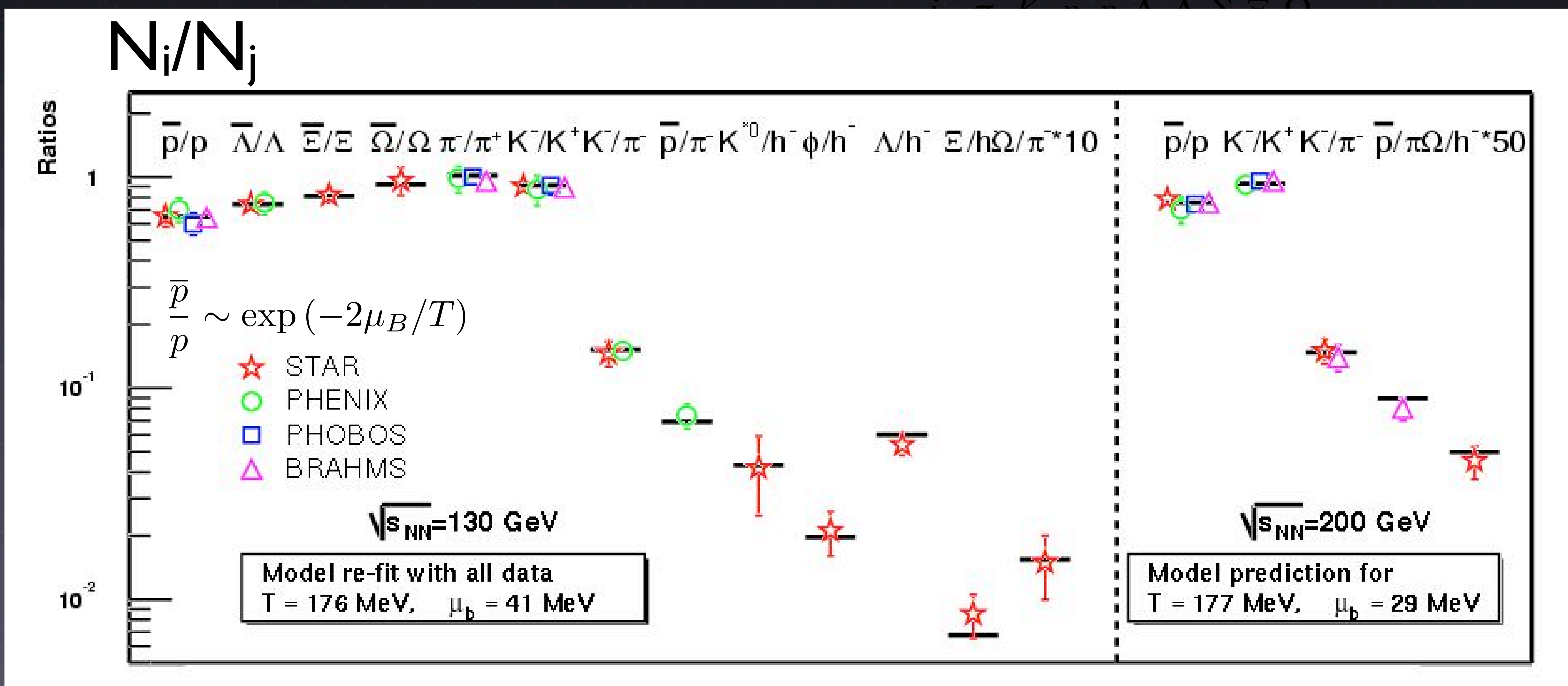
We only need to ~double the energy density of a nucleon!

Particle Ratios

T	Chemical freezeout temperature
μ_B	Baryochemical potential (when you have more matter than antimatter!)

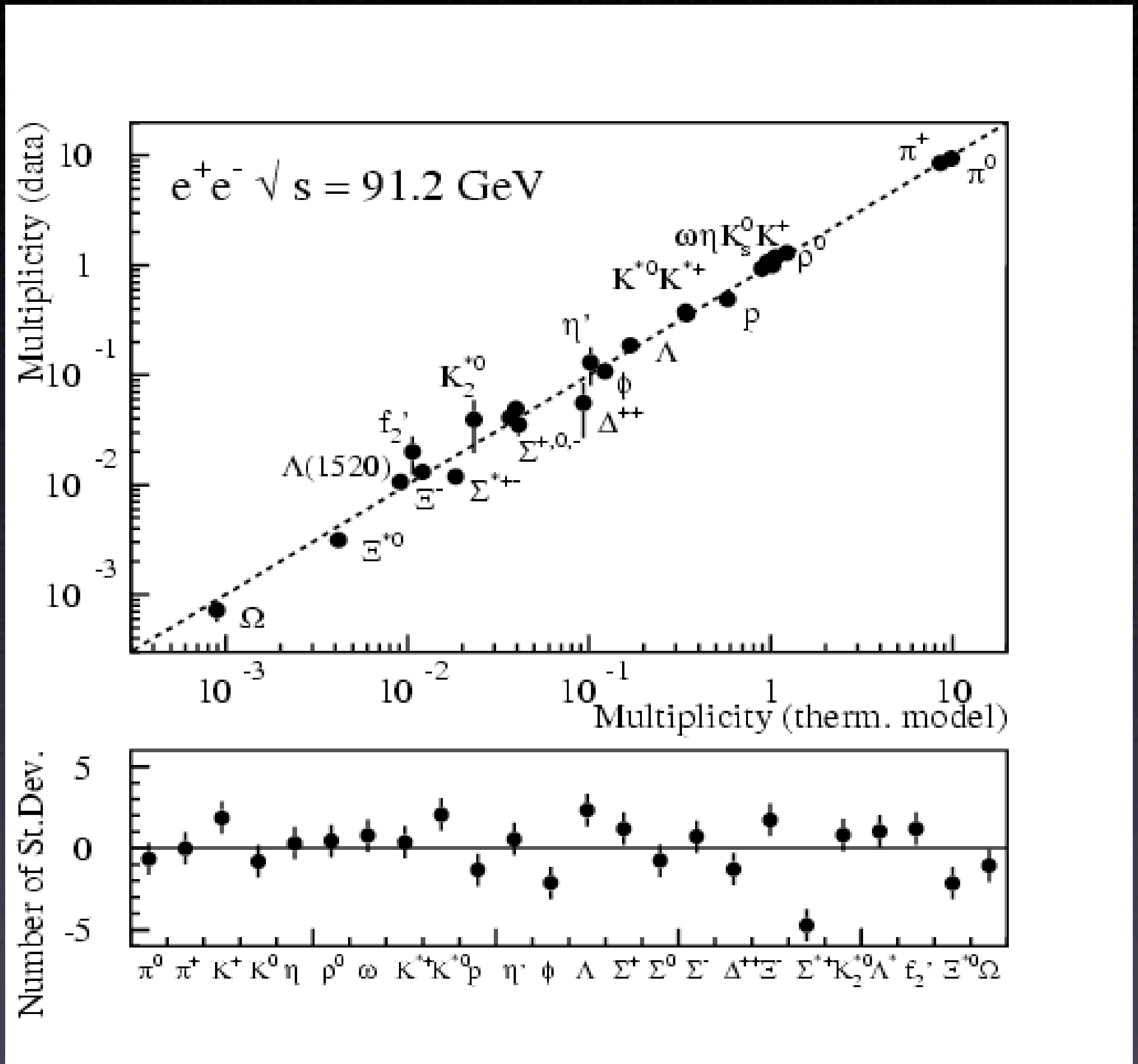
$$N_i \propto V \int \frac{d^3p}{(2\pi)^3} \frac{1}{e^{(\sqrt{p^2+m^2}-\mu_B)/T} \pm 1}$$

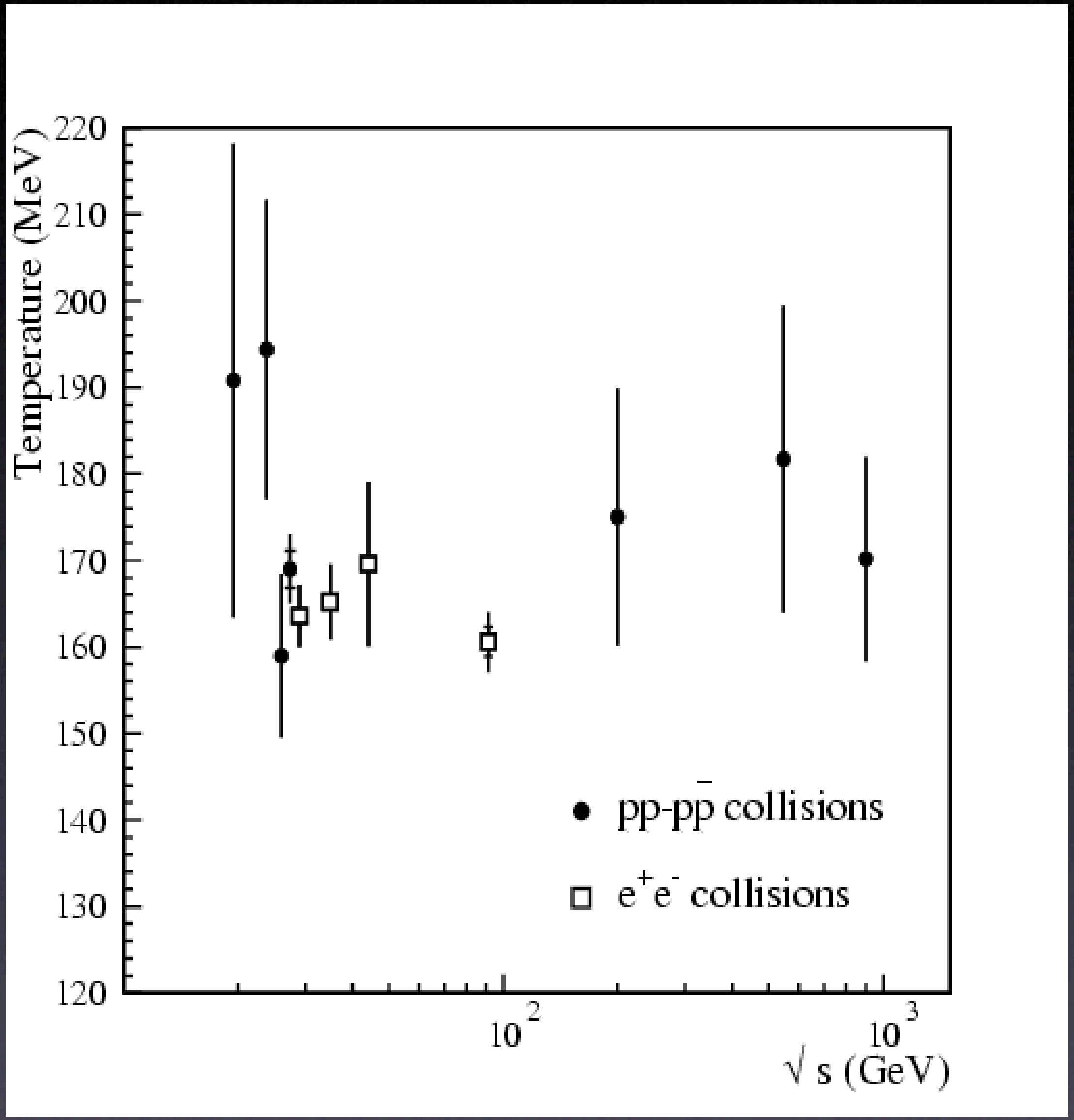
Blackbody spectrum



Braun-Munzinger, Magestro, Stachel (2001)

Thermalization Everywhere?

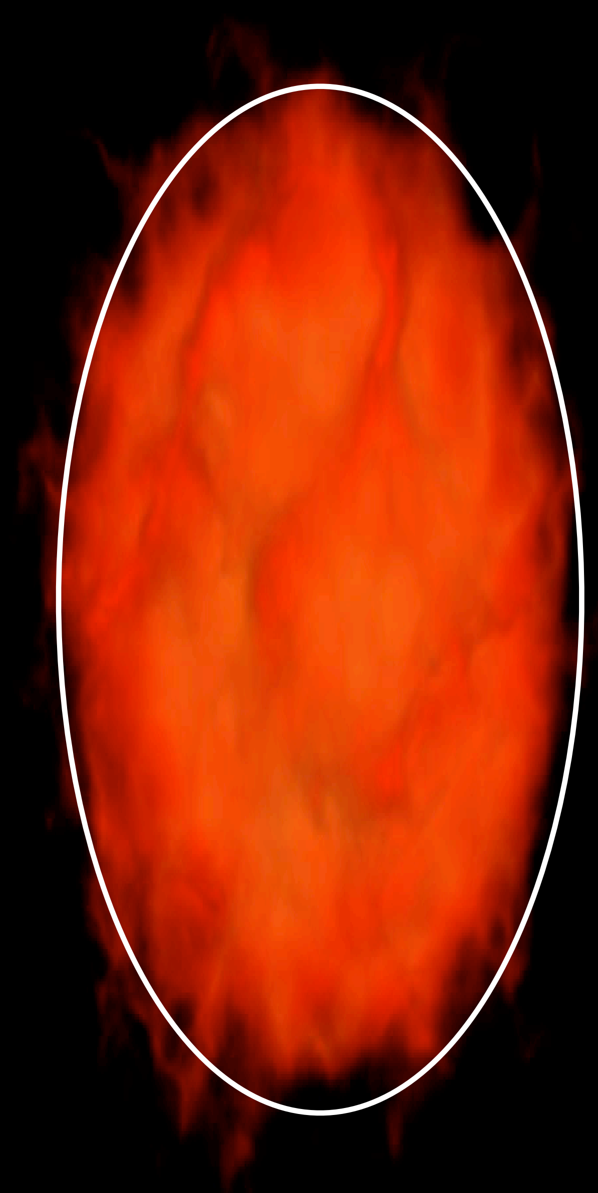


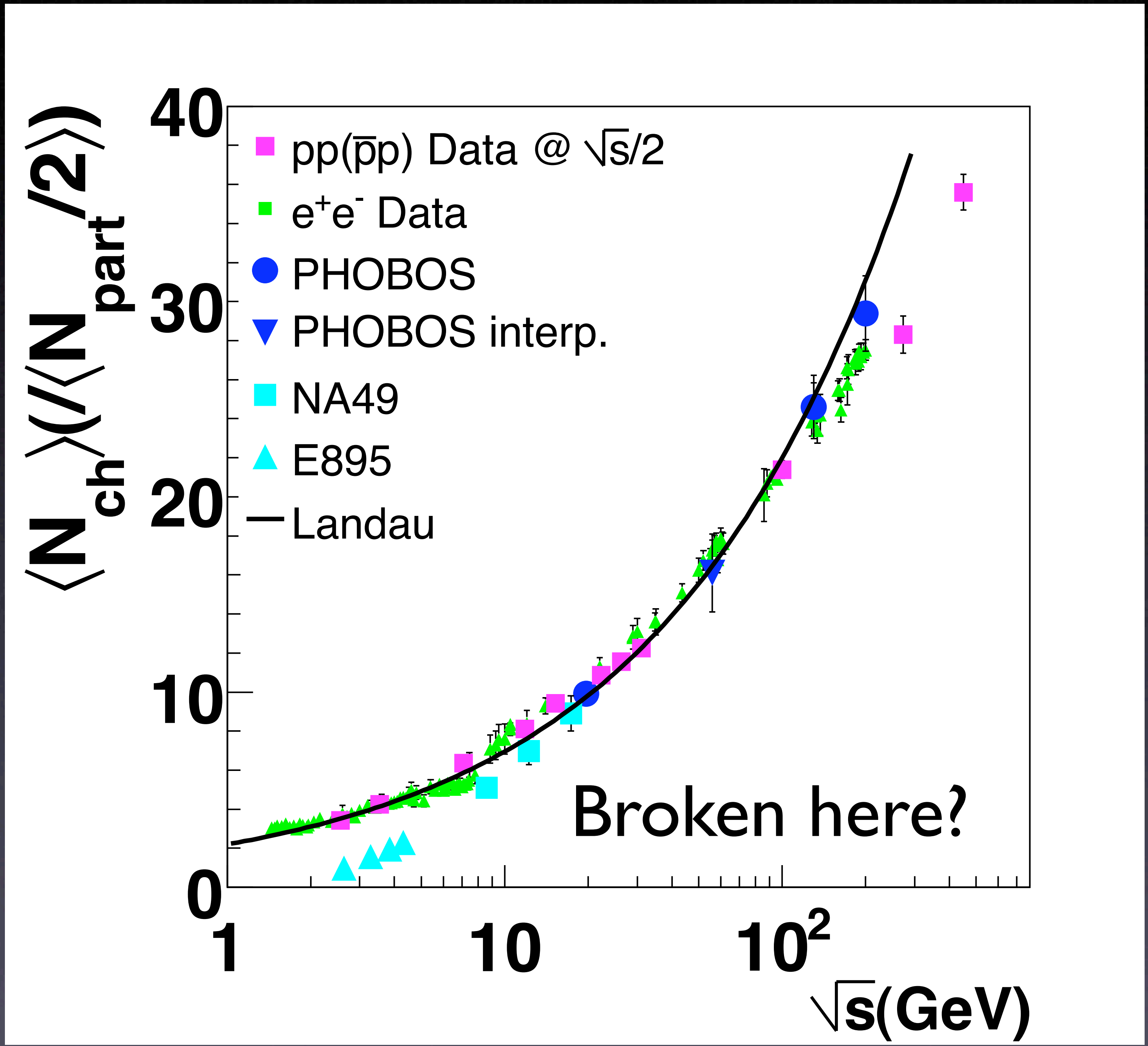


Statistical hadronization seems to work everywhere, with similar temperatures over a wide range of collision energy!

F. Becattini

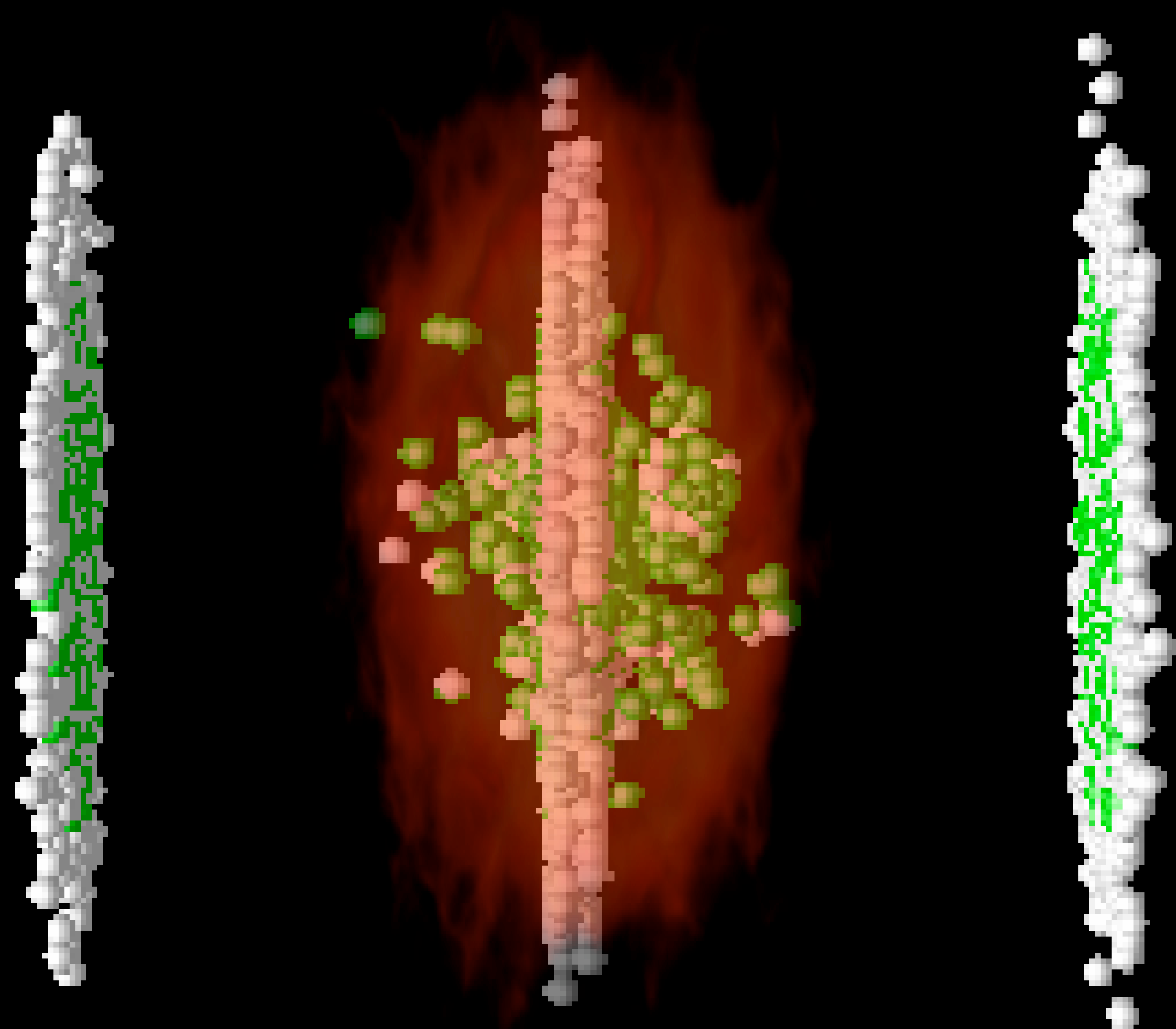
Fermi-Landau Entropy





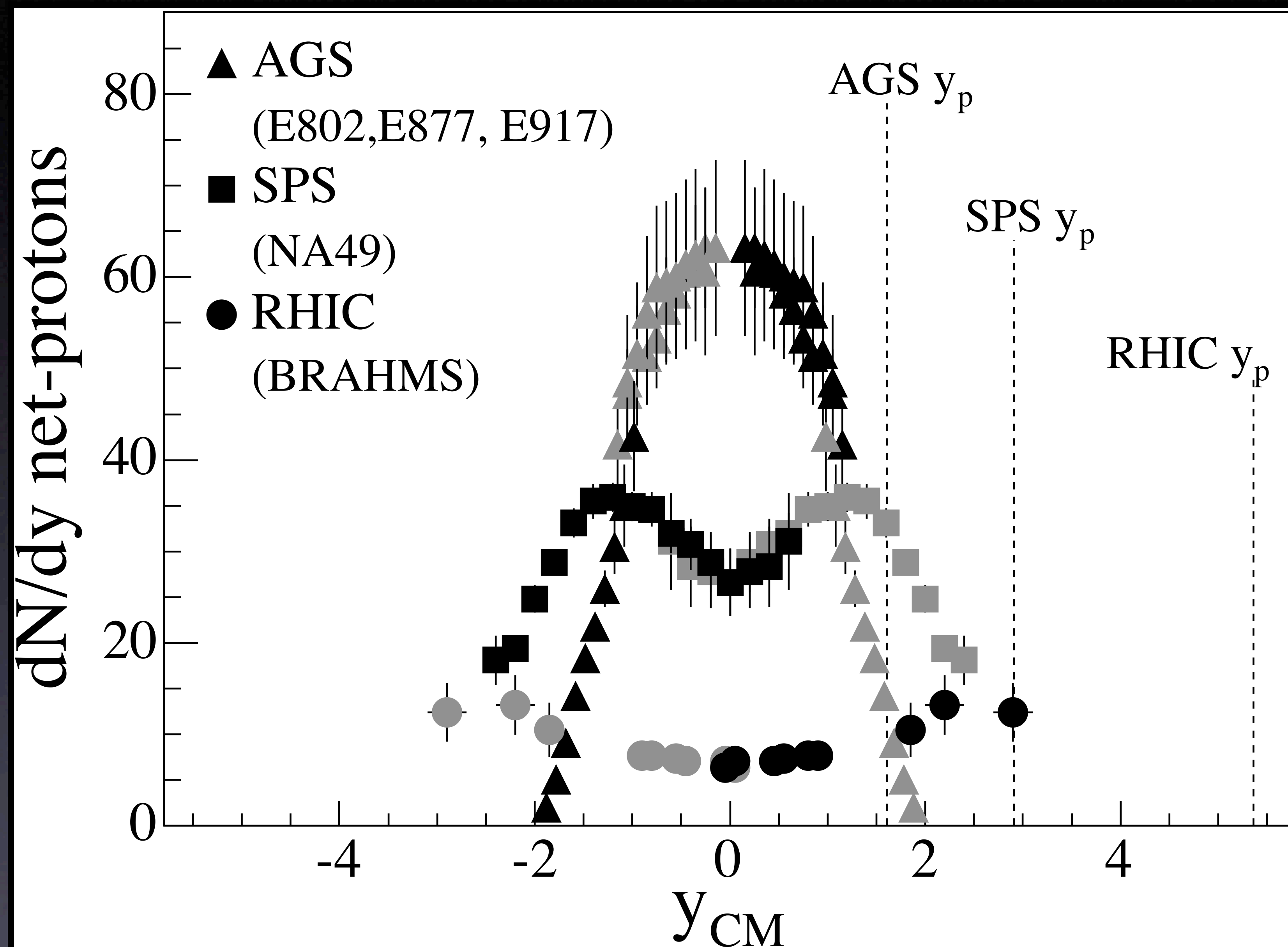
Direct relationship between energy density and entropy (which rises quite <u>slowly</u>)

What about the Baryons?



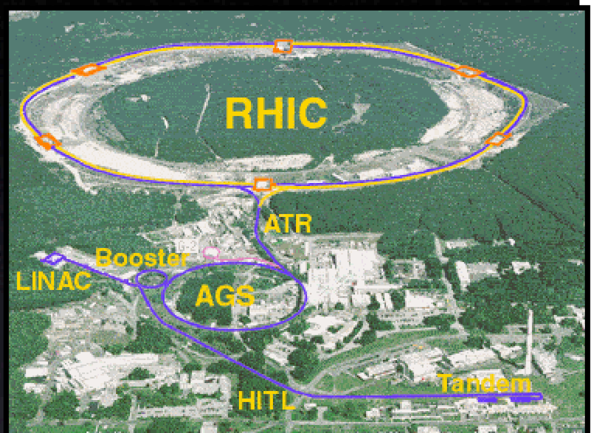
Nucleons are “baryons”, which are conserved and much heavier than pions - an uneven trade!

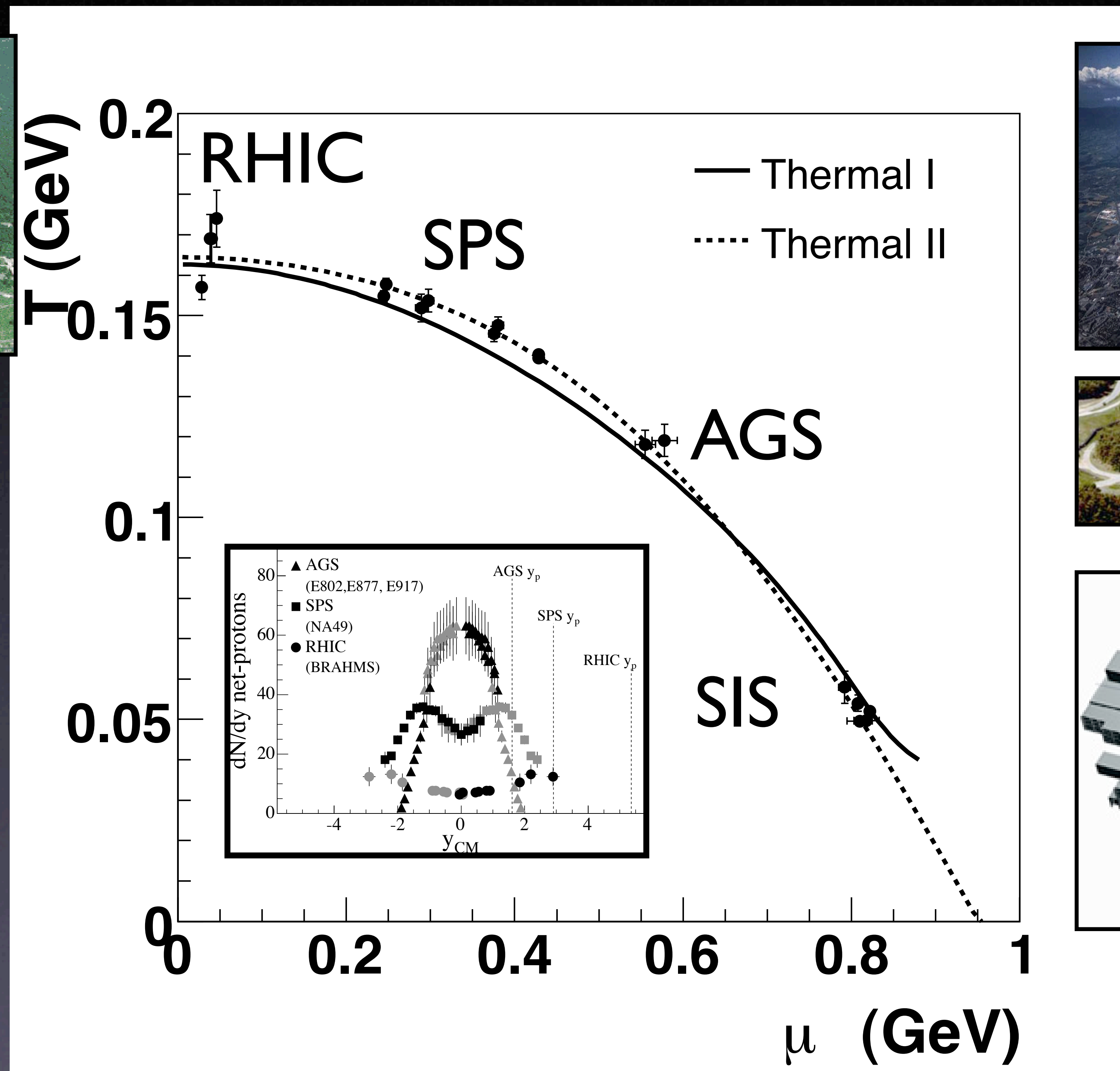
“Baryochemistry”

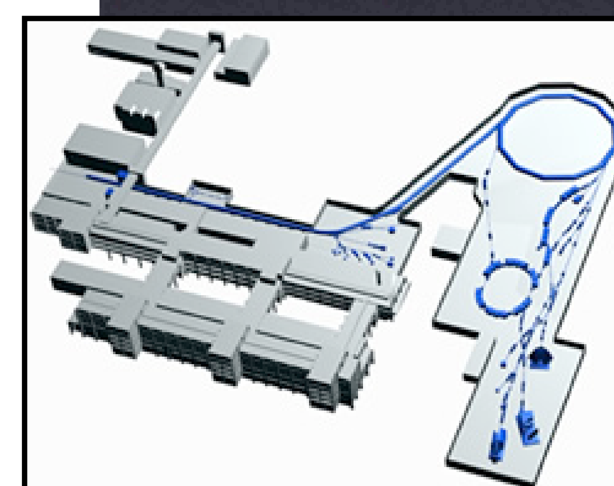


At low energies, the participating baryons are found to “pile up”, with most of them nearly at rest.
At higher energies, they seem to have appreciable velocity...

“Phase Diagram”







As beam energy decreases, increases chemical potential

Baryochemistry

In equilibrium:

$$G = E + PV - TS = \mu_B N_B$$

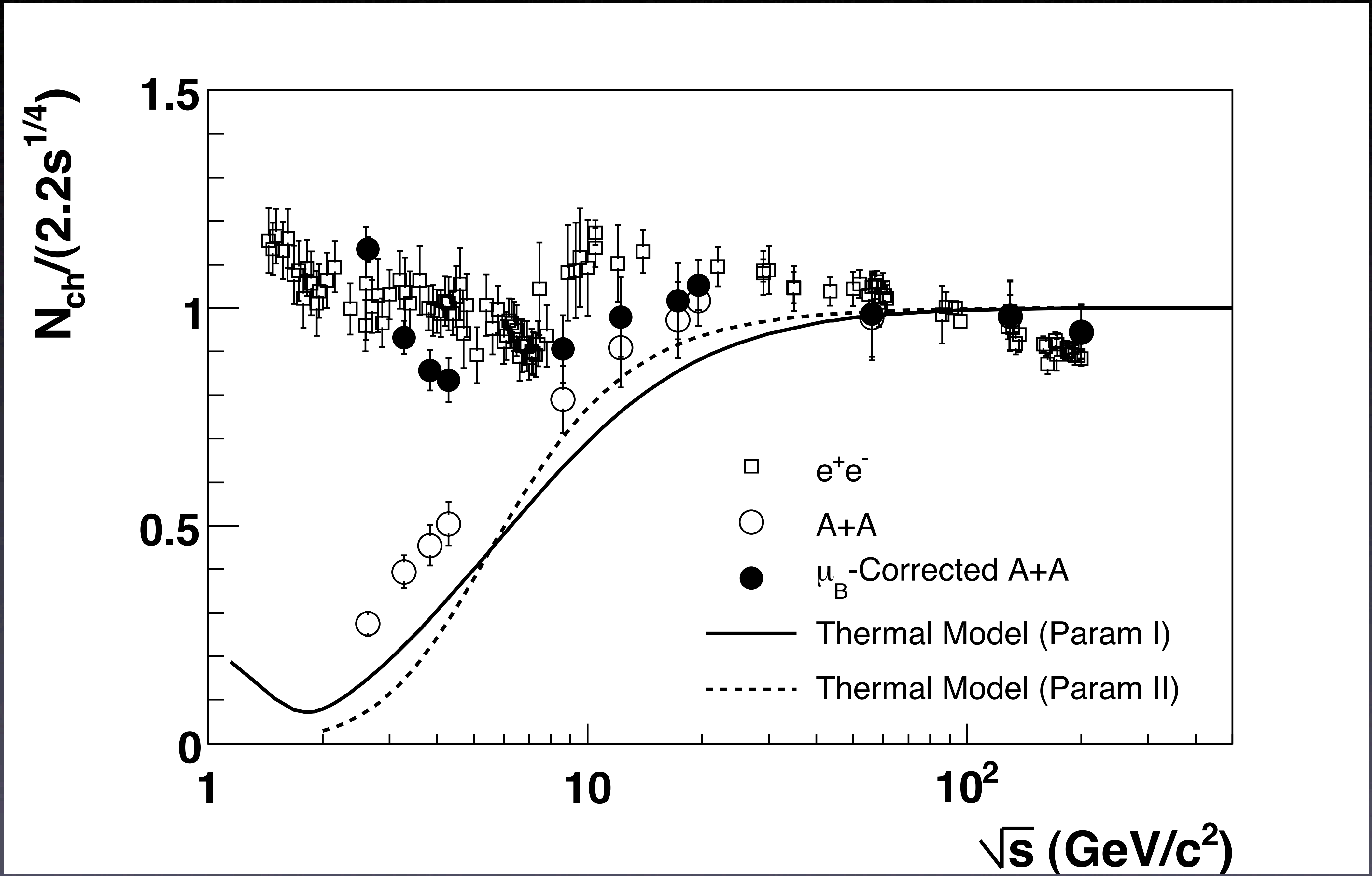
Rearranges to:

$$S = \frac{E + PV}{T} - \frac{\mu_B N_B}{T}$$

So chemical potential reduces entropy, and thus total multiplicity:

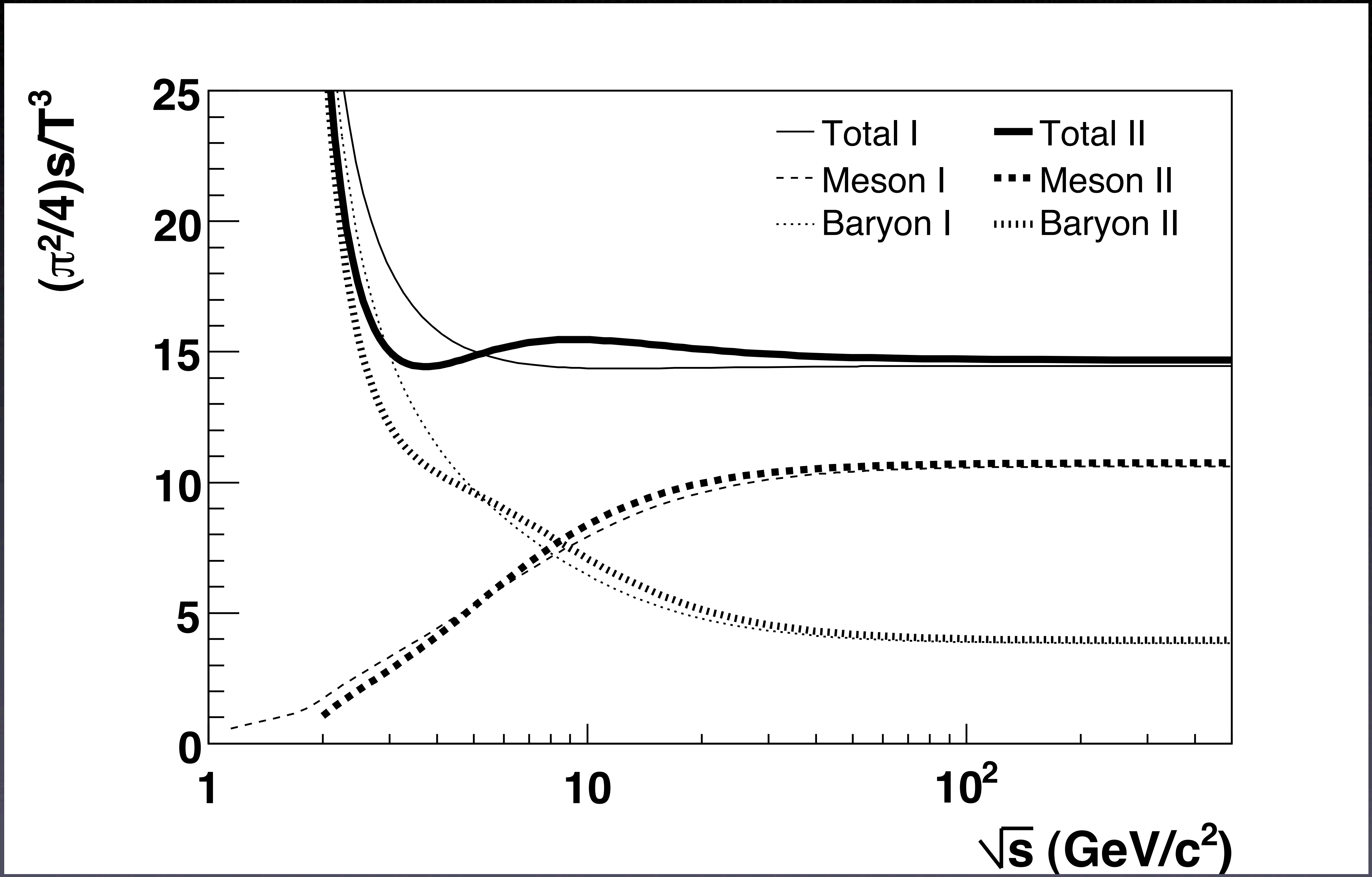
$$\Delta \frac{N_{ch}}{N_{part}/2} \propto \frac{\mu_B}{T}$$

Application to Data

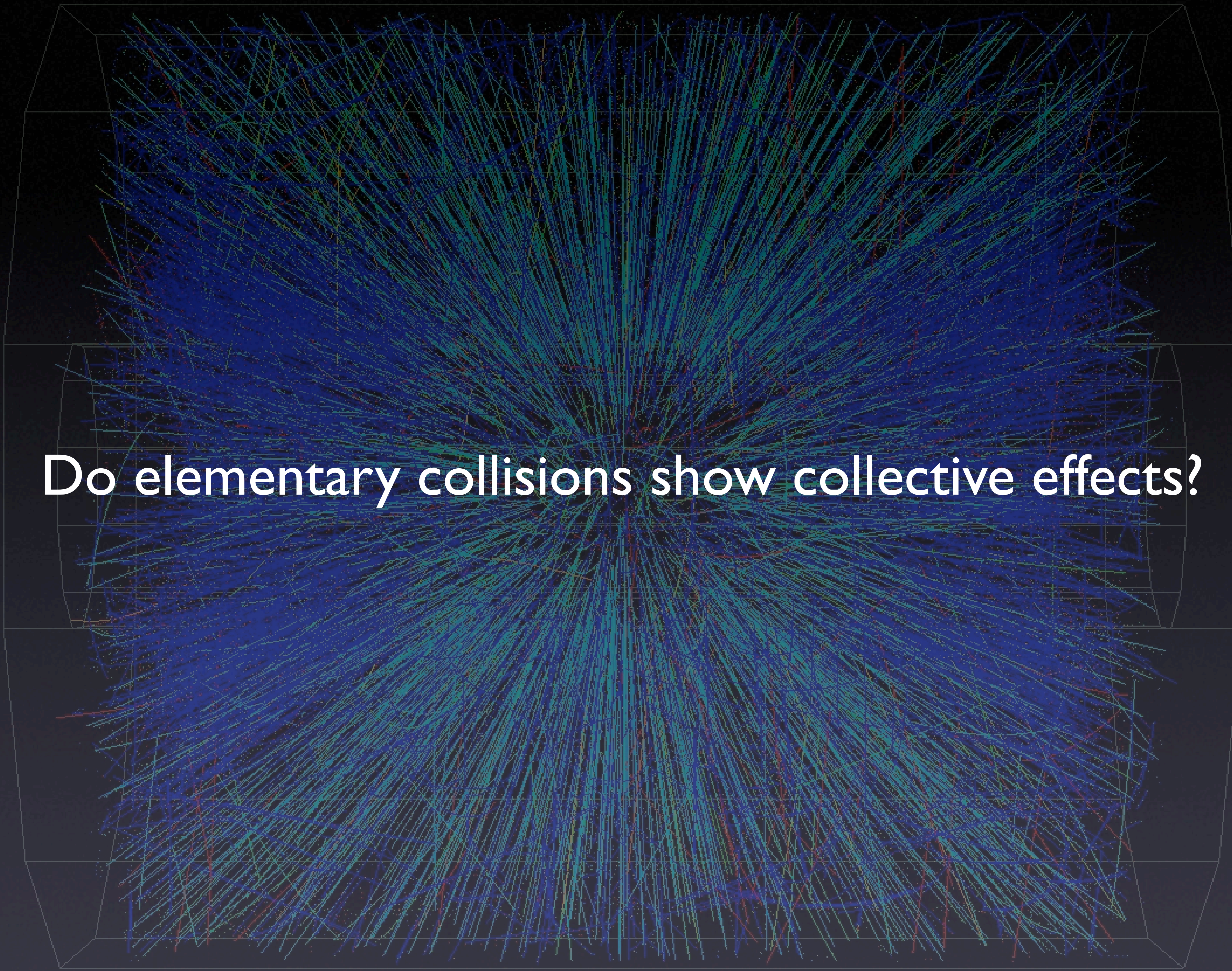


Qualitative understanding of relationship between baryon density and entropy!

Baryons vs. Mesons

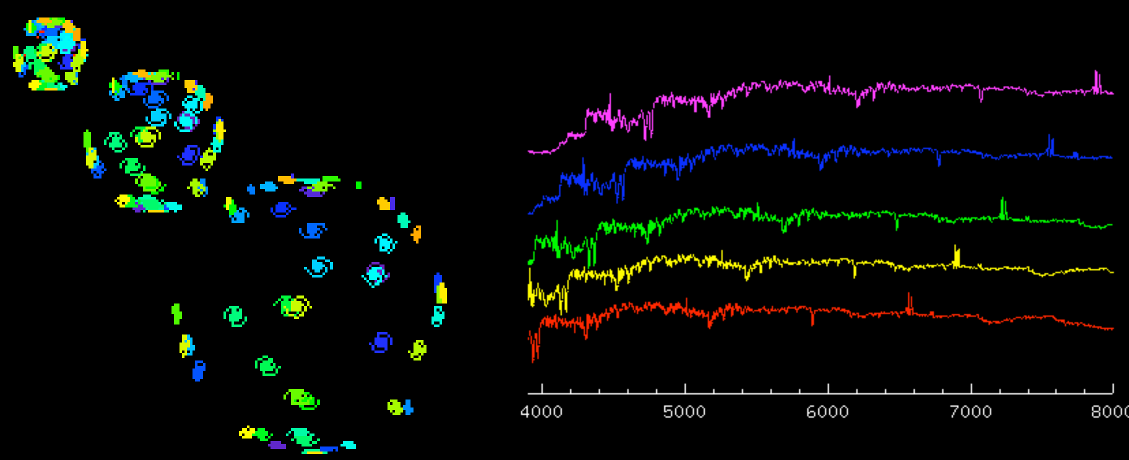


As energy changes, s/T^3 (degrees of freedom) remain constant!

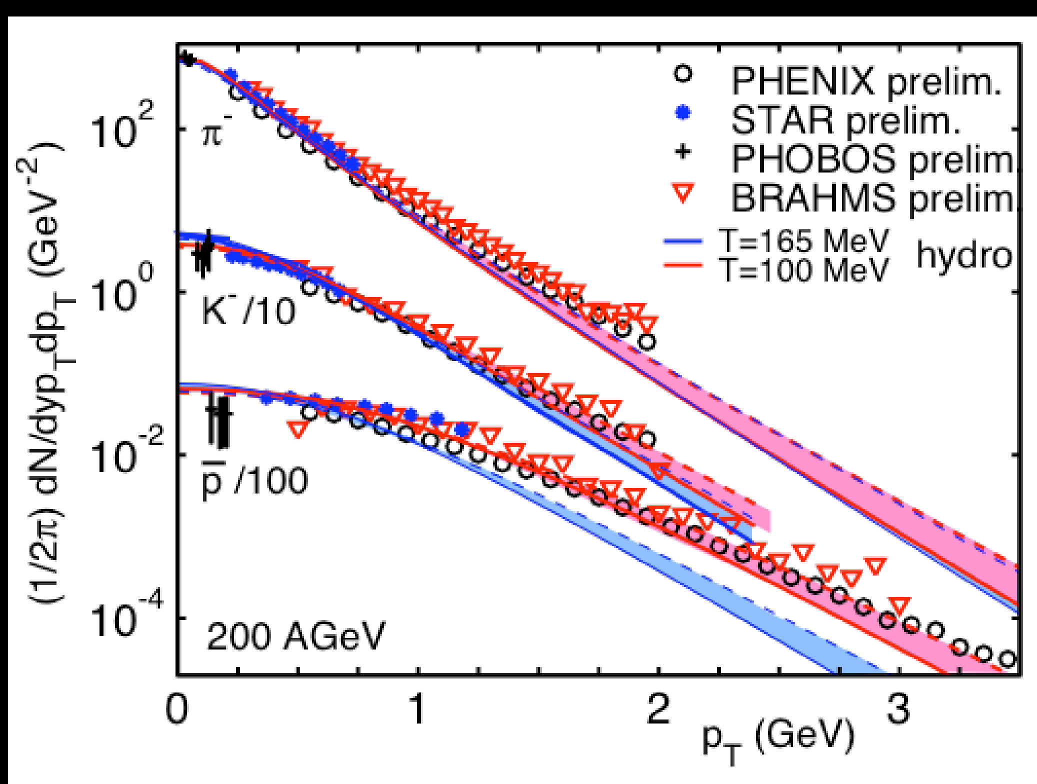


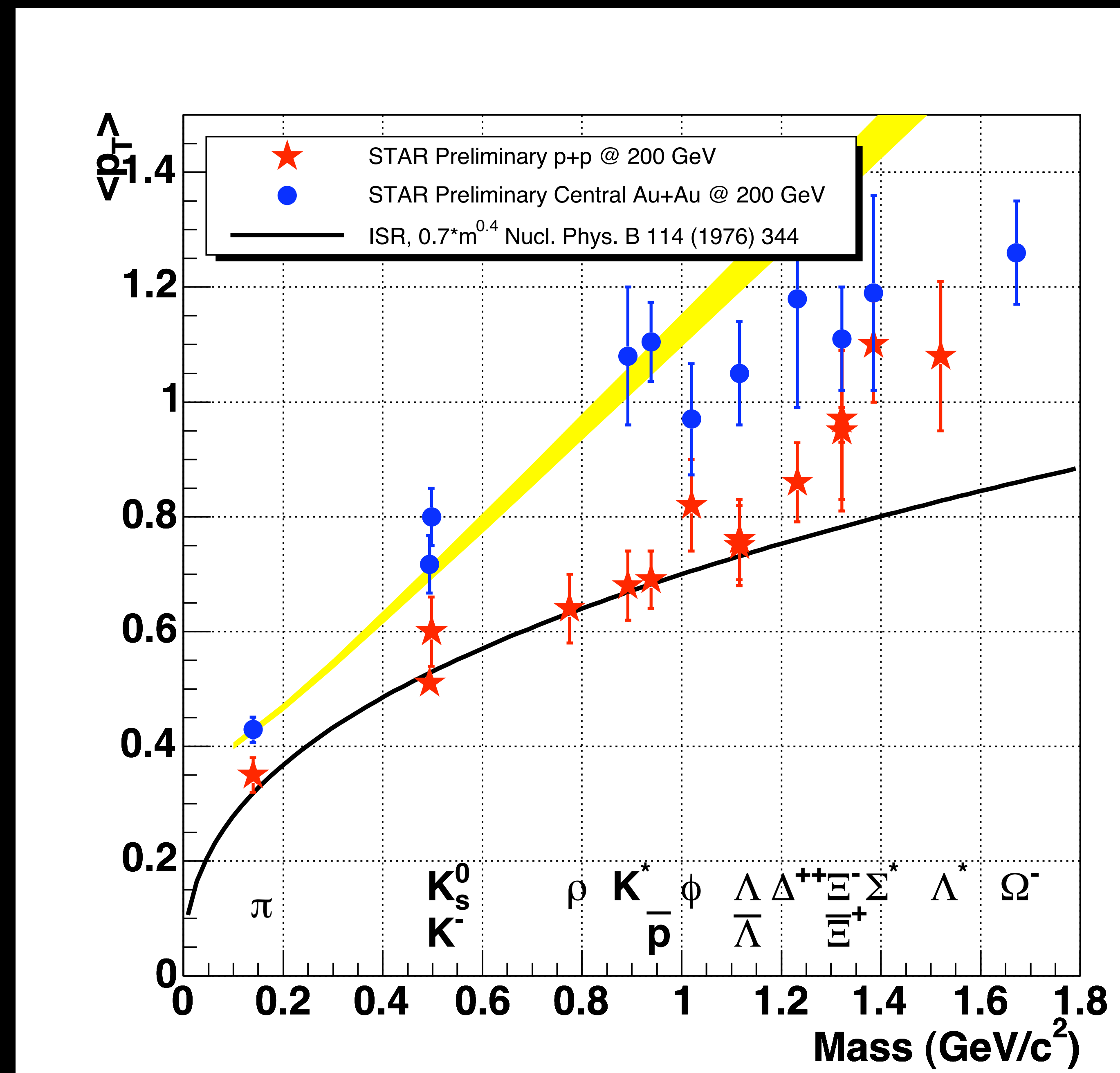
Do elementary collisions show collective effects?

Radial Expansion, Redux



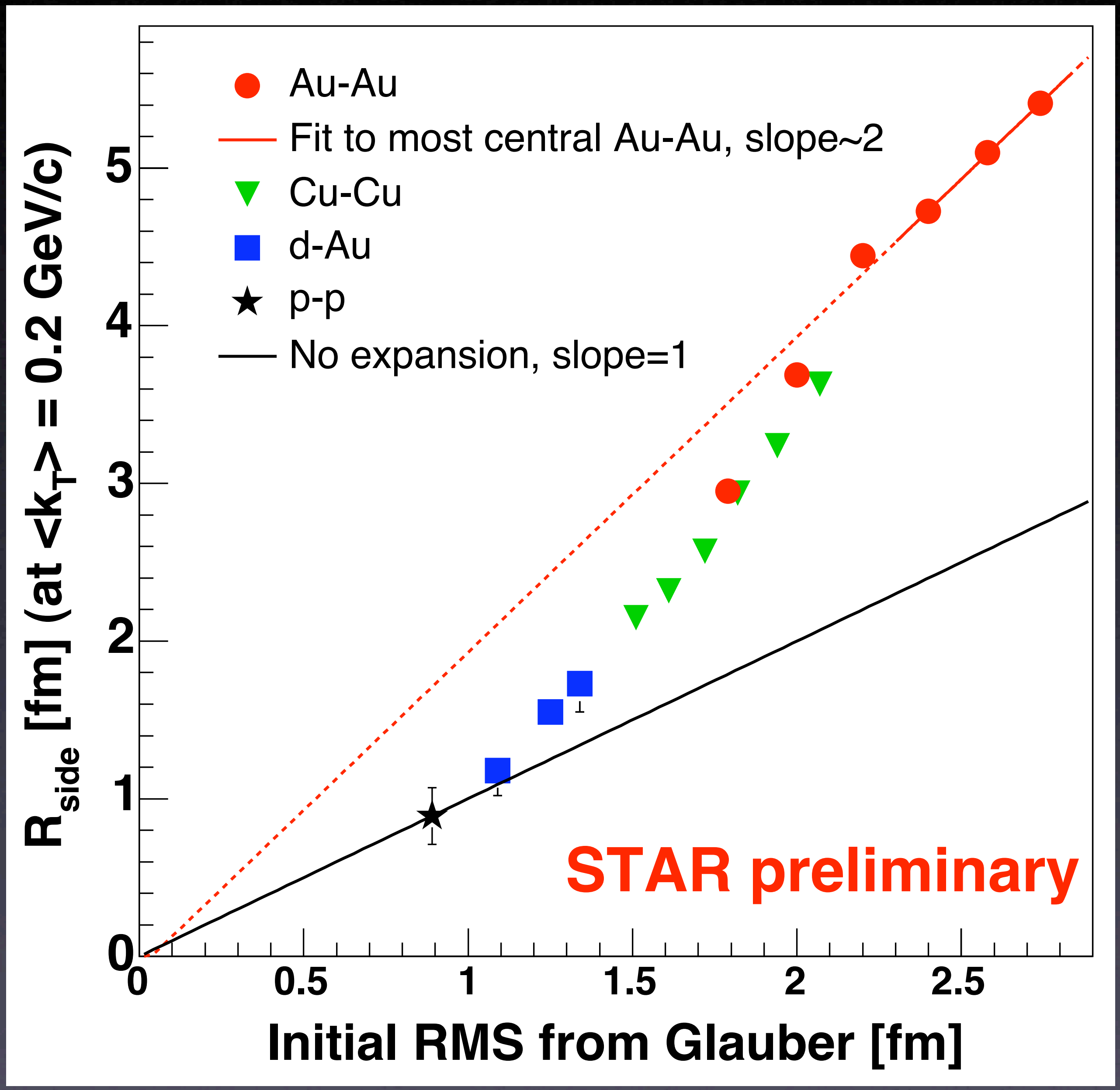
$$T_{eff} = T_0 + m\beta_T^2$$

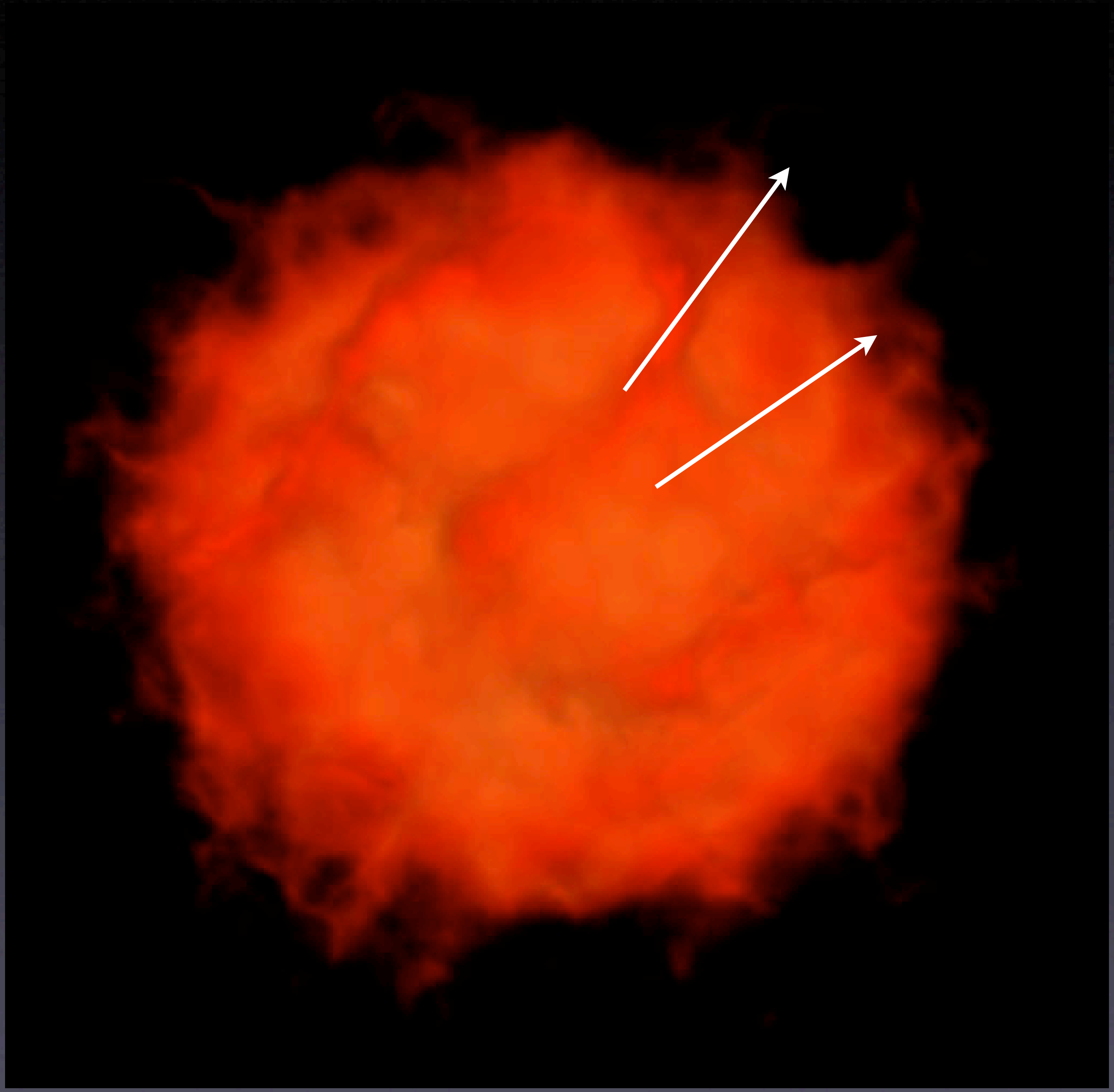




"Blue shifting" seen in A+A <u>and</u> p+p (STAR)

Radial Expansion, contd.

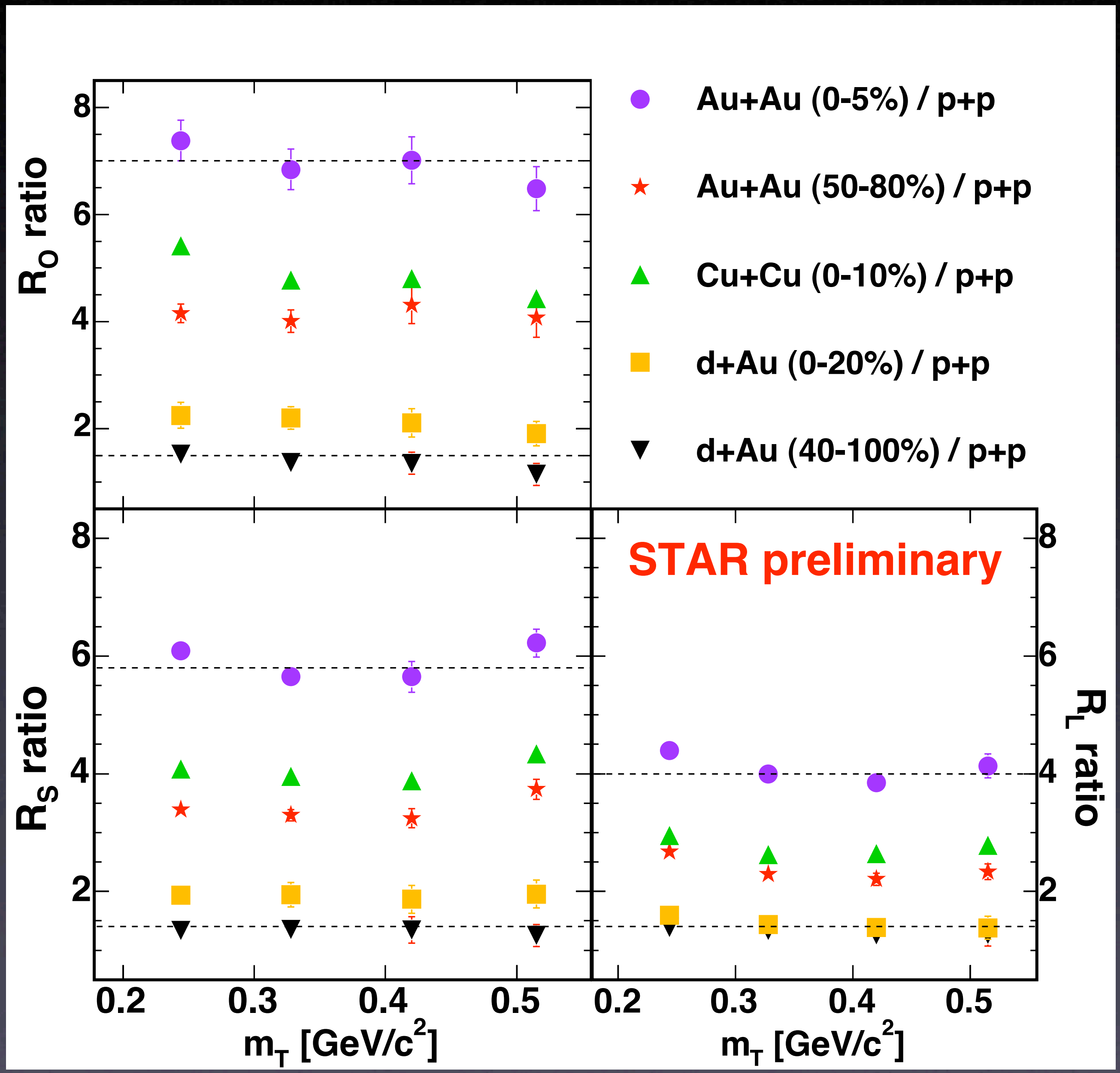


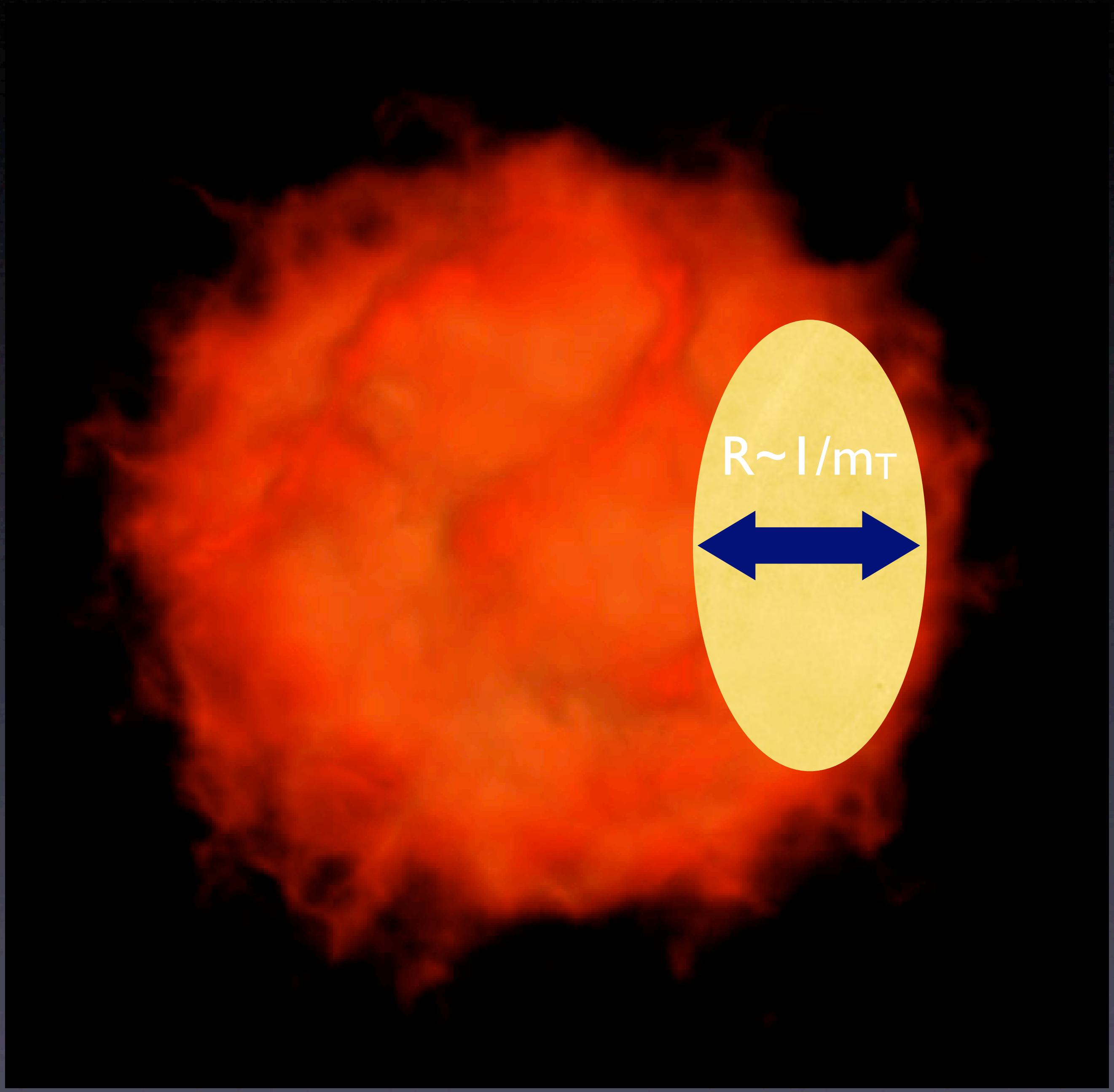


STAR Data on HBT Radii in p+p, d+Au and Au+Au

Continuum of expansion-like behavior

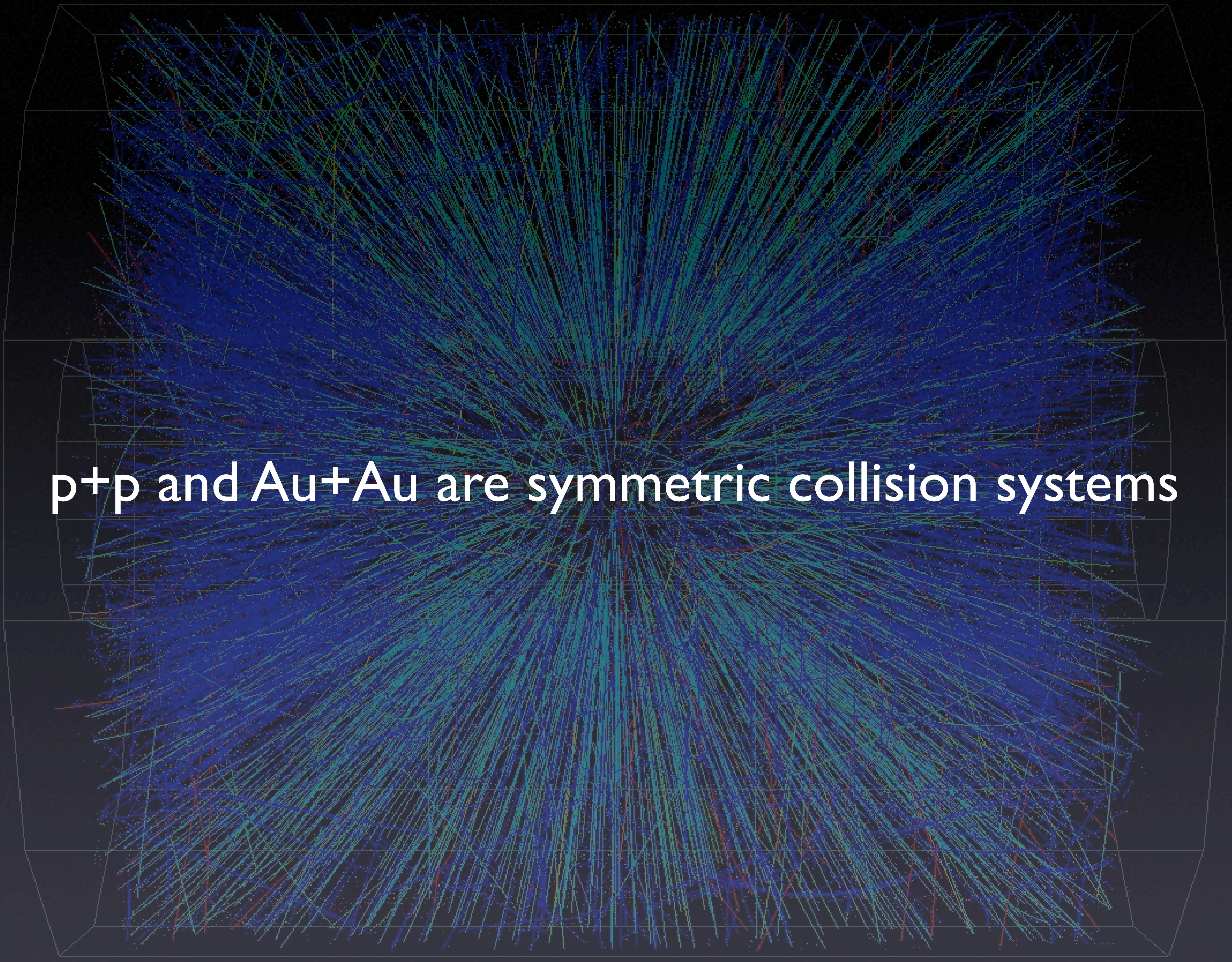
Radial Expansion, contd.





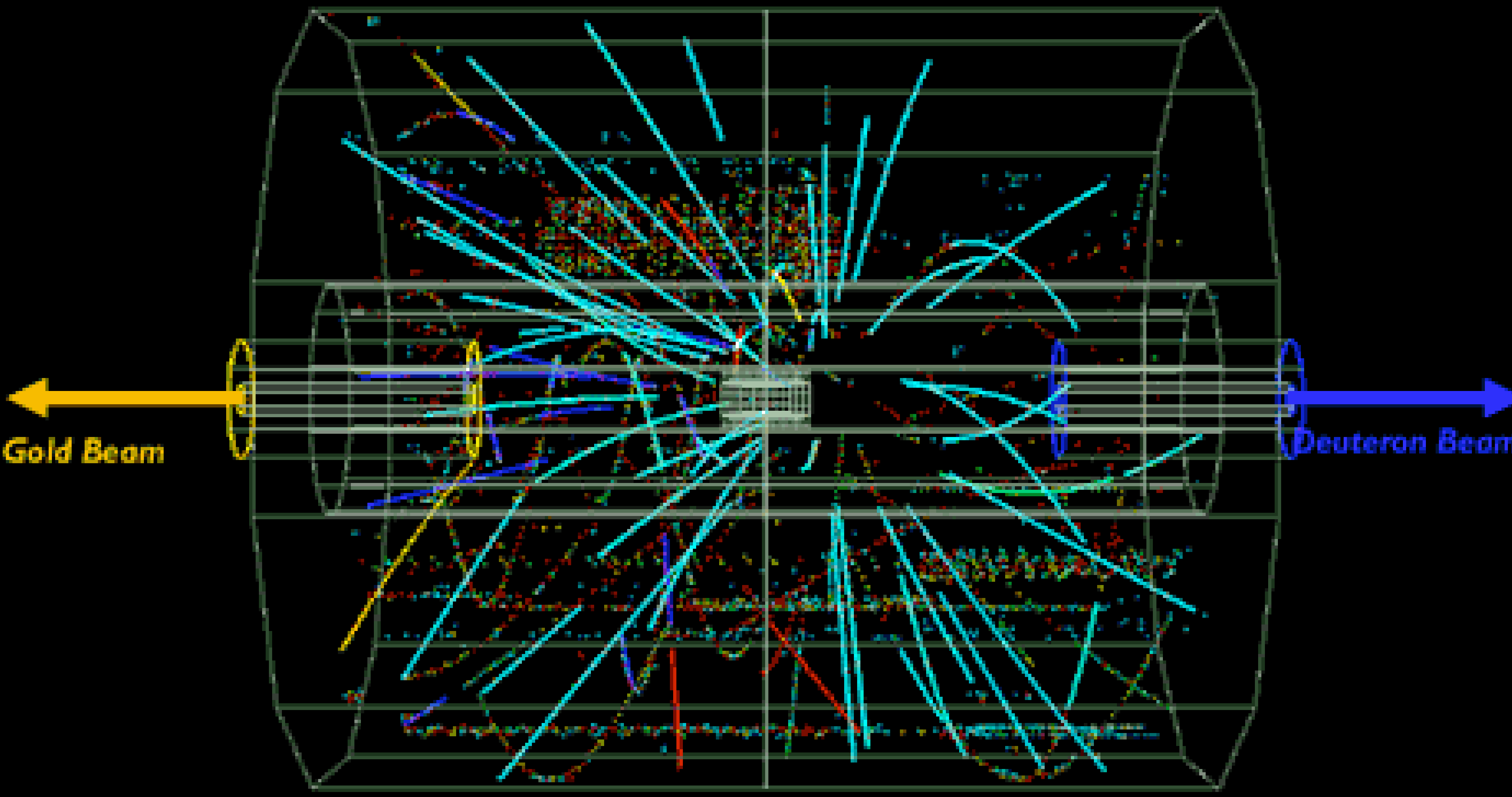
Ratios of A+A/p+p "scale", i.e. same relative change vs. m_T

Continuum of expansion-like behavior



p+p and Au+Au are symmetric collision systems

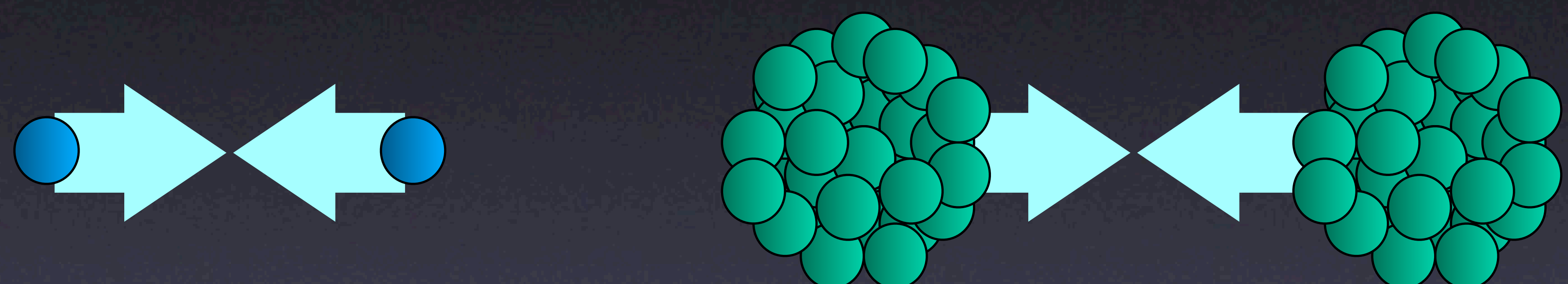
Asymmetric Systems



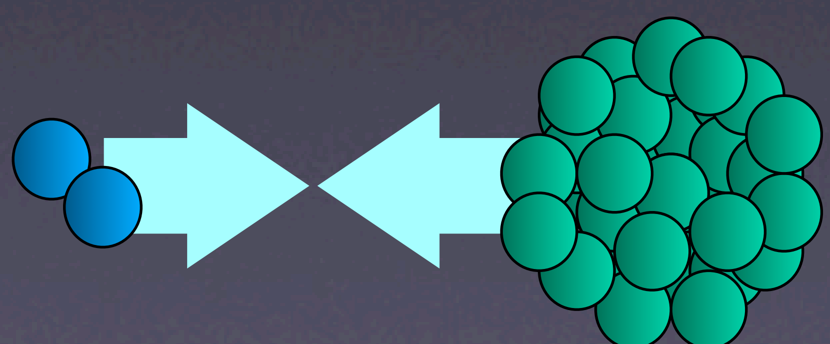
deuteron-gold collision in STAR

Asymmetric Systems

If early energy density controls
entropy and longitudinal dynamics,
then not surprising things look similar in smaller
and larger symmetric systems (p+p, A+A, e+e-)



How do things behave in an asymmetric system?



Centrality Bins in d+Au

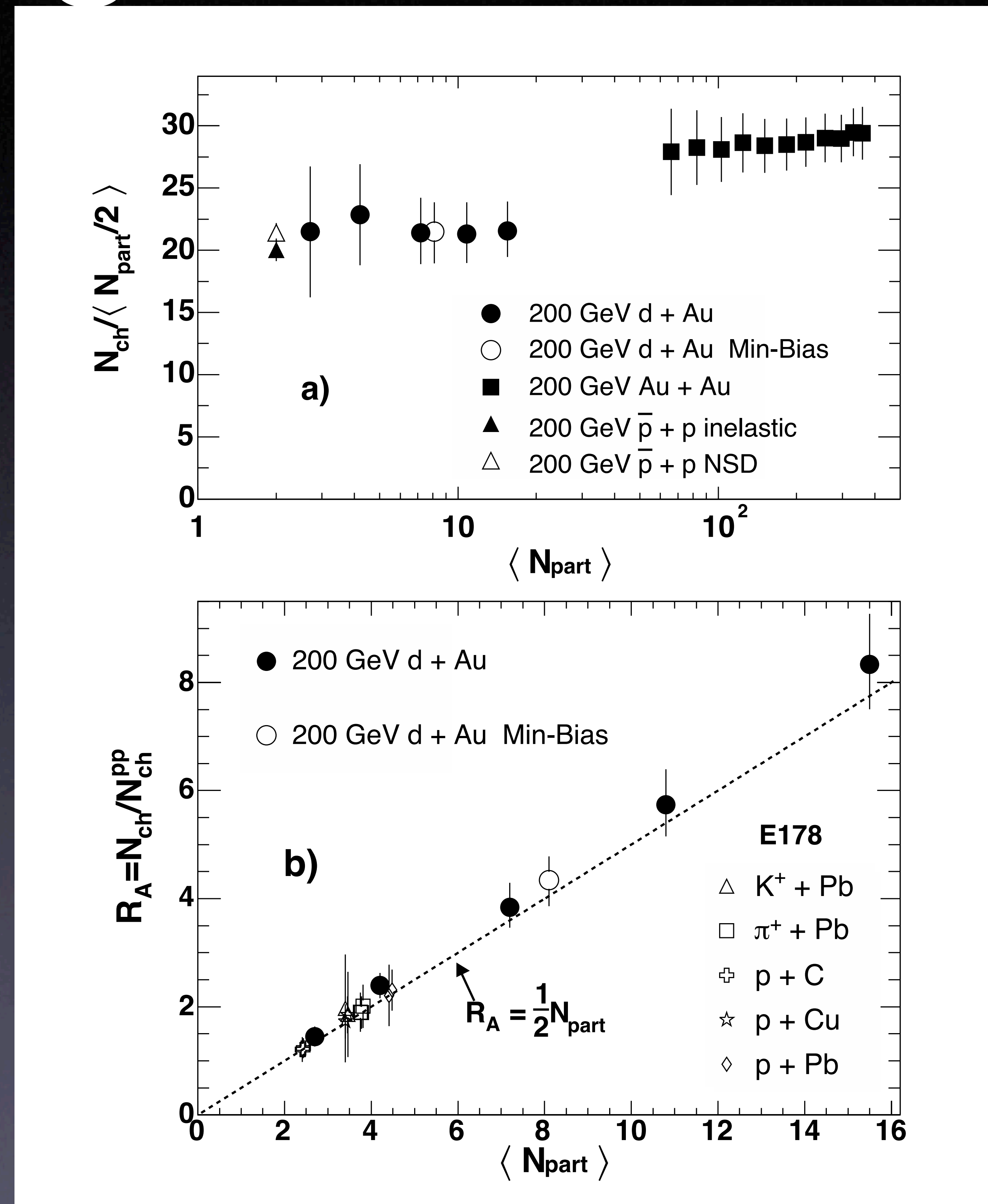
Cent. (%)	$\langle N_{part}^{Au} \rangle$	$\langle N_{part}^{d} \rangle$	$\langle N_{coll} \rangle$	$N_{\vert\eta\vert<5.4}^{ch}$	N_{Tot}^{ch}
0–20	13.5 ± 1.0	2.0 ± 0.1	14.7 ± 0.9	157 ± 10	167^{+14}_{-11}
20–40	8.9 ± 0.7	1.9 ± 0.1	9.8 ± 0.7	109 ± 7	115^{+10}_{-8}
40–60	5.4 ± 0.6	1.7 ± 0.2	5.9 ± 0.6	74 ± 5	77^{+7}_{-5}
60–80	2.9 ± 0.5	1.4 ± 0.2	3.1 ± 0.6	46 ± 3	48^{+3}_{-3}
80–100	1.6 ± 0.4	1.1 ± 0.2	1.7 ± 0.5	28 ± 3	29^{+3}_{-3}
Min-Bias	6.6 ± 0.5	1.7 ± 0.1	7.1 ± 0.5	82 ± 6	87^{+7}_{-6}
50-70	3.9 ± 0.6	1.6 ± 0.2	4.2 ± 0.6	59 ± 4	62^{+5}_{-4}

N_{part} scaling in d+Au

d+Au is also constant per $N_{part}/2$

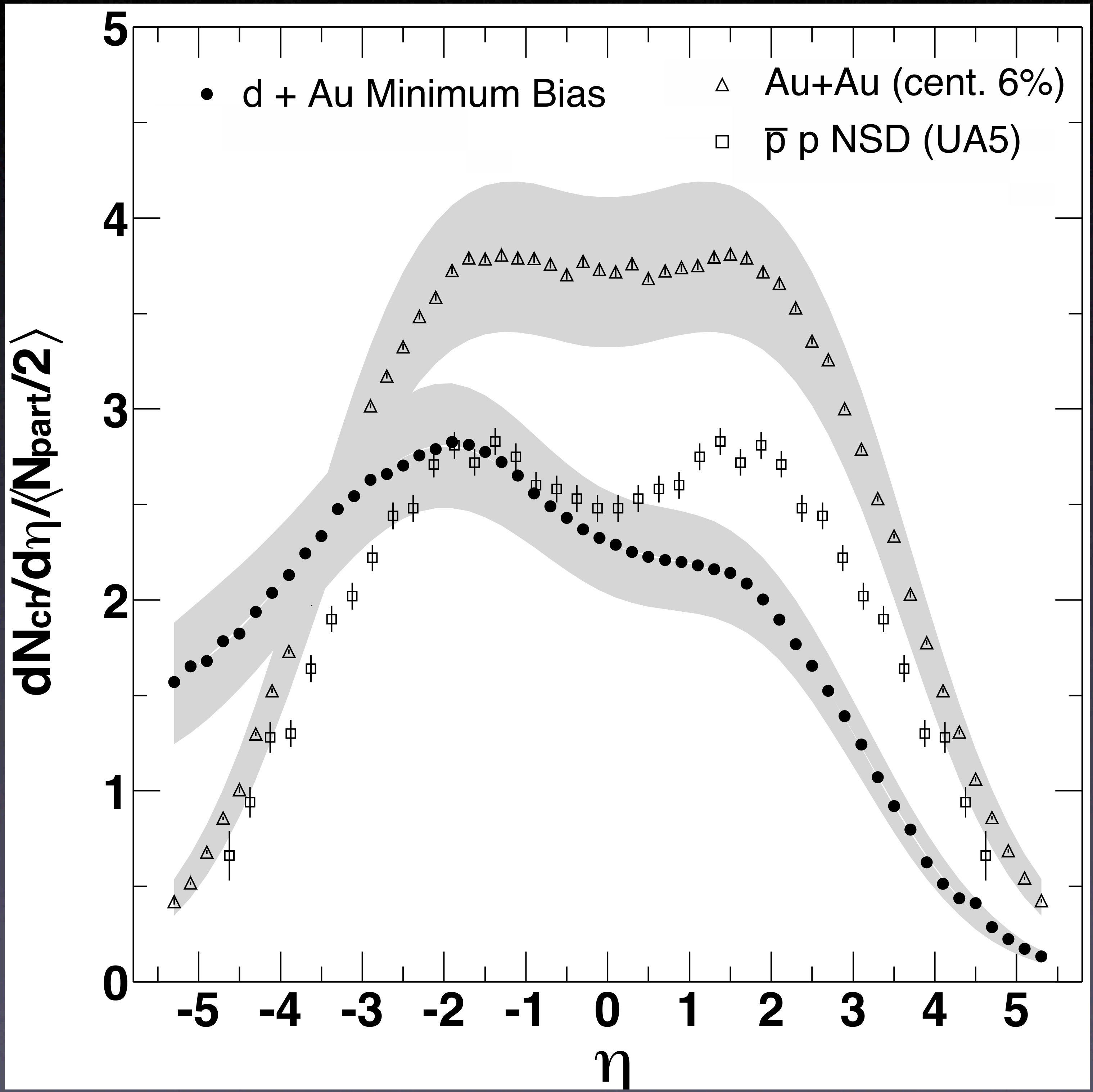
"wounded nucleon scaling" seen at lower energies

But one sees a "jump" between p+p/d+Au and Au+Au
(a hint about how stopping occurs?)

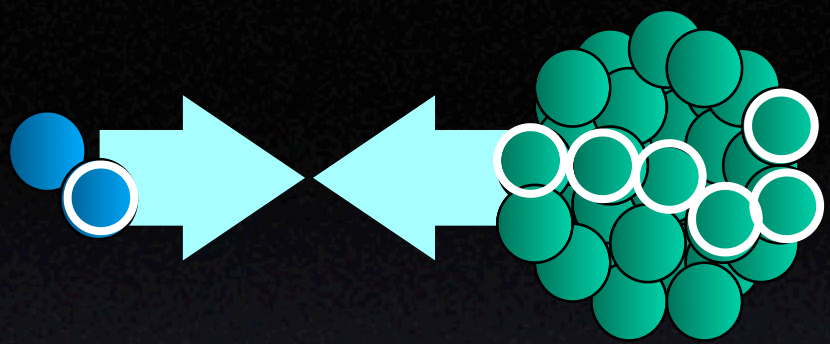


d+Au vs. p+p & Au+Au

Although the integrated multiplicity per wounded nucleon is similar to p+p, the particles seem to be “shifted” in phase space!



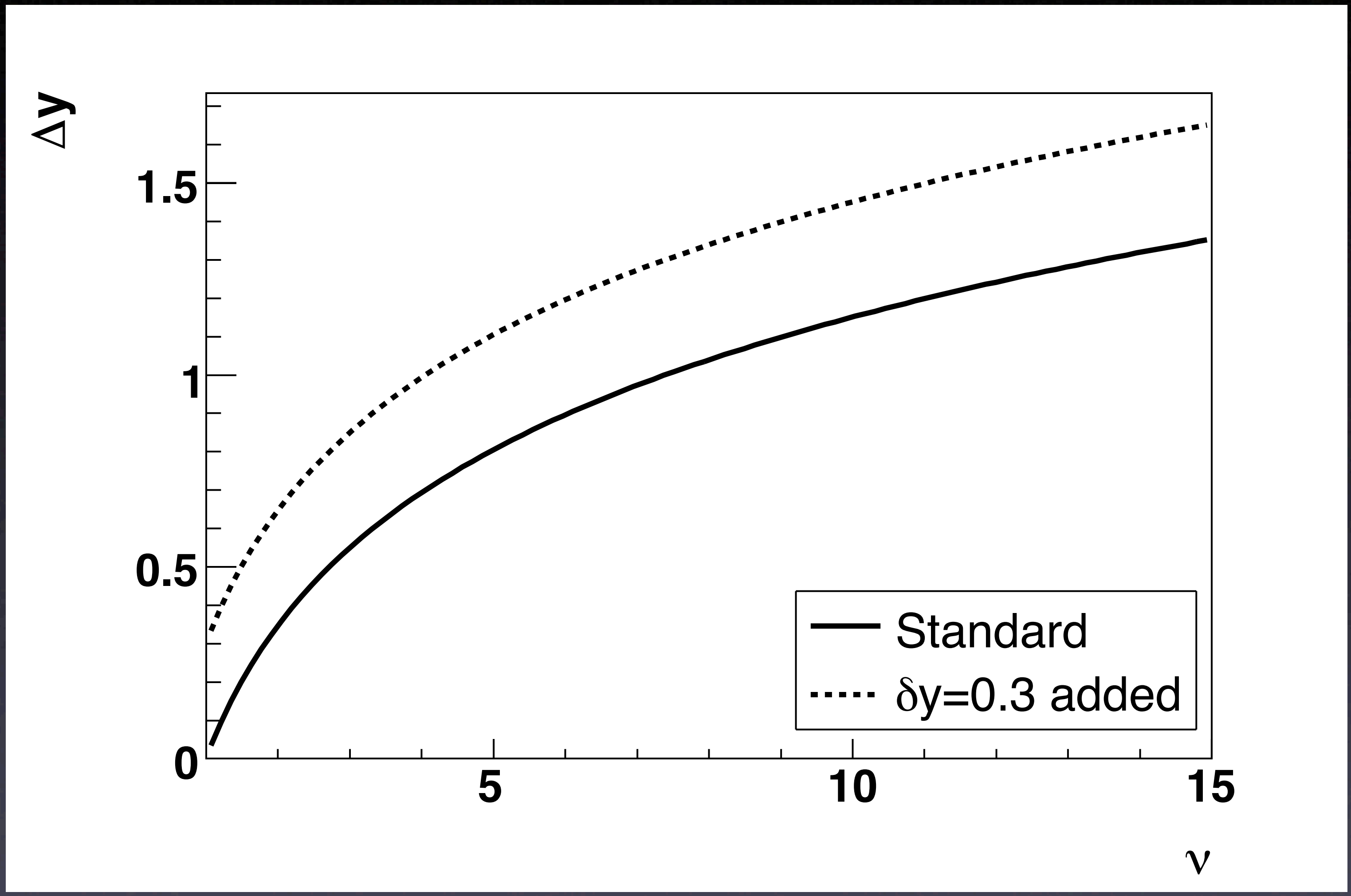
Shifted CMS



Colliding system
is not at rest
in CMS system

$$\Delta y = -\frac{1}{2}\ln\left(\frac{N_{part}^{Au}}{N_{part}^{d}}\right) + \delta y$$

$$= -\ln\left(\sqrt{\nu}\right) + \delta y$$



One might expect contributions to rapidity shift from spectators or transverse dynamics, so could consider "extra" component δy

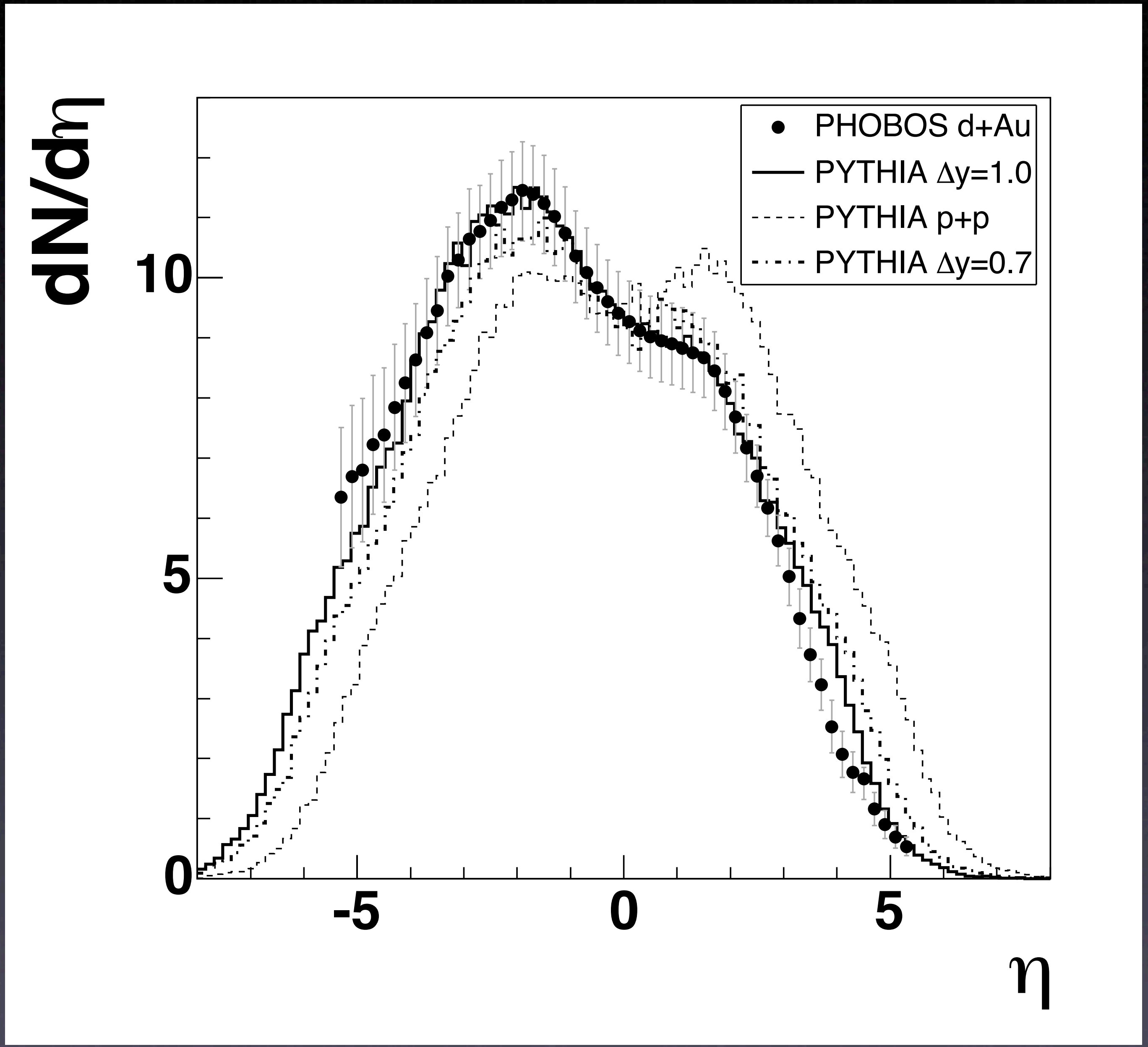
A "Trivial" Model

Take charged particles in PYTHIA distributed as dN/dy

Shift them in <u>rapidity</u> by Δy

Recalculate the η of each particle and make a $dN/d\eta$ spectrum

Scale up by $N_{part}/2$



Surprisingly efficient description of d+Au data

Comparisons to p+p

$$R_\eta = \frac{\left.\frac{dN}{d\eta}\right._{d+Au}}{\left.\frac{dN}{d\eta}\right._{p+p}}$$

Predictions from the 1970's thought that the ratio between p+A and p+p should be "wedge-shaped"

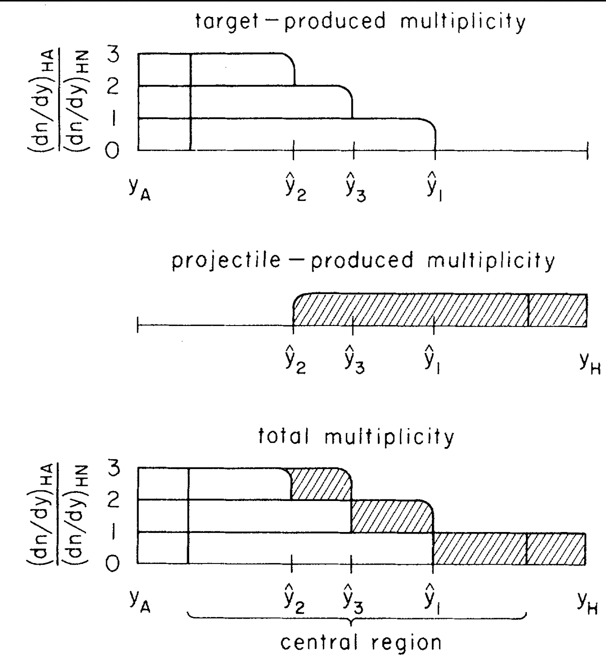


FIG. 1. Idealized multiplicity distribution for an H–A collision with $\bar{\nu} = 3$ inelastic excitations. The y_i are uniformly distributed in rapidity and can be produced in any sequence.

$= [\bar{\nu}/(\bar{\nu}+1)]Y_c$. Thus we obtain, for the ratio of multiplicities in the central region,

$$\langle n\rangle_{HA}/\langle n\rangle_{HN} = \bar{\nu}/2 + \bar{\nu}/(\bar{\nu}+1), \qquad (2)$$

where the only dependence on the projectile H is through the definition of $\bar{\nu}$.

The distribution of particles averaged over events produced from the excitation of the nuclear partons is wedge shaped. The ratio of distributions $R_A(y)$ in the central region for hadron-nucleon to hadron-nucleus collisions is simply ($y_A \equiv 0$)

$$\frac{(dn/dy)_{HA}}{(dn/dy)_{HN}} = \bar{\nu}\left(1 - \frac{y}{Y_c}\right) + \left[1 - \left(1 - \frac{y}{Y_c}\right)^{\bar{\nu}}\right]. \qquad (3)$$

Brodsky, Gunion, Kuhn (1977)

“Shift” Model of R_η

1. Direct calculation with PYTHIA:

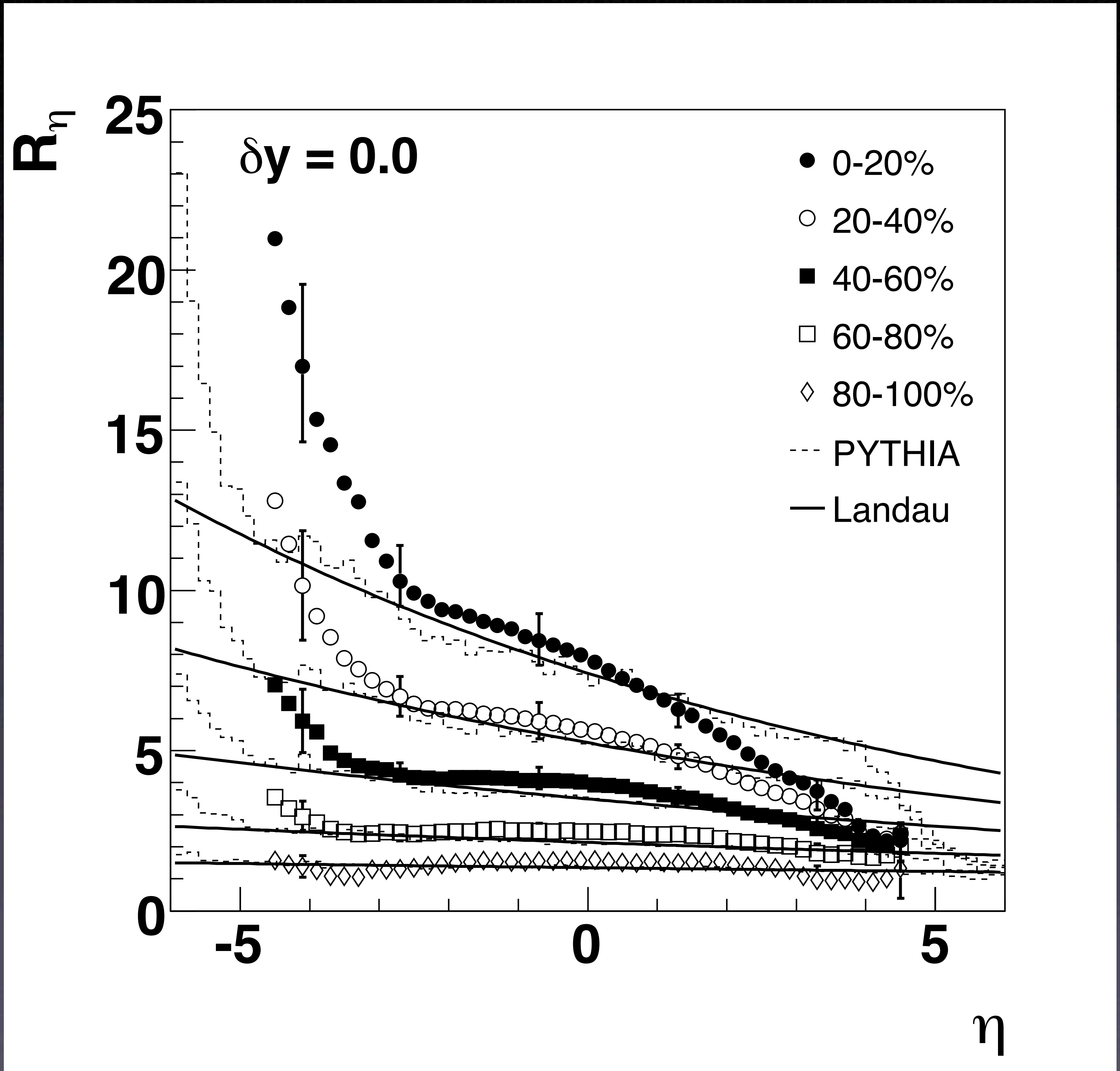
Recalculate pseudorapidity distribution after shifting rapidity, and scaling by $N_{part}/2$,then divide by p+p

2. Shift “Landau-inspired” gaussians

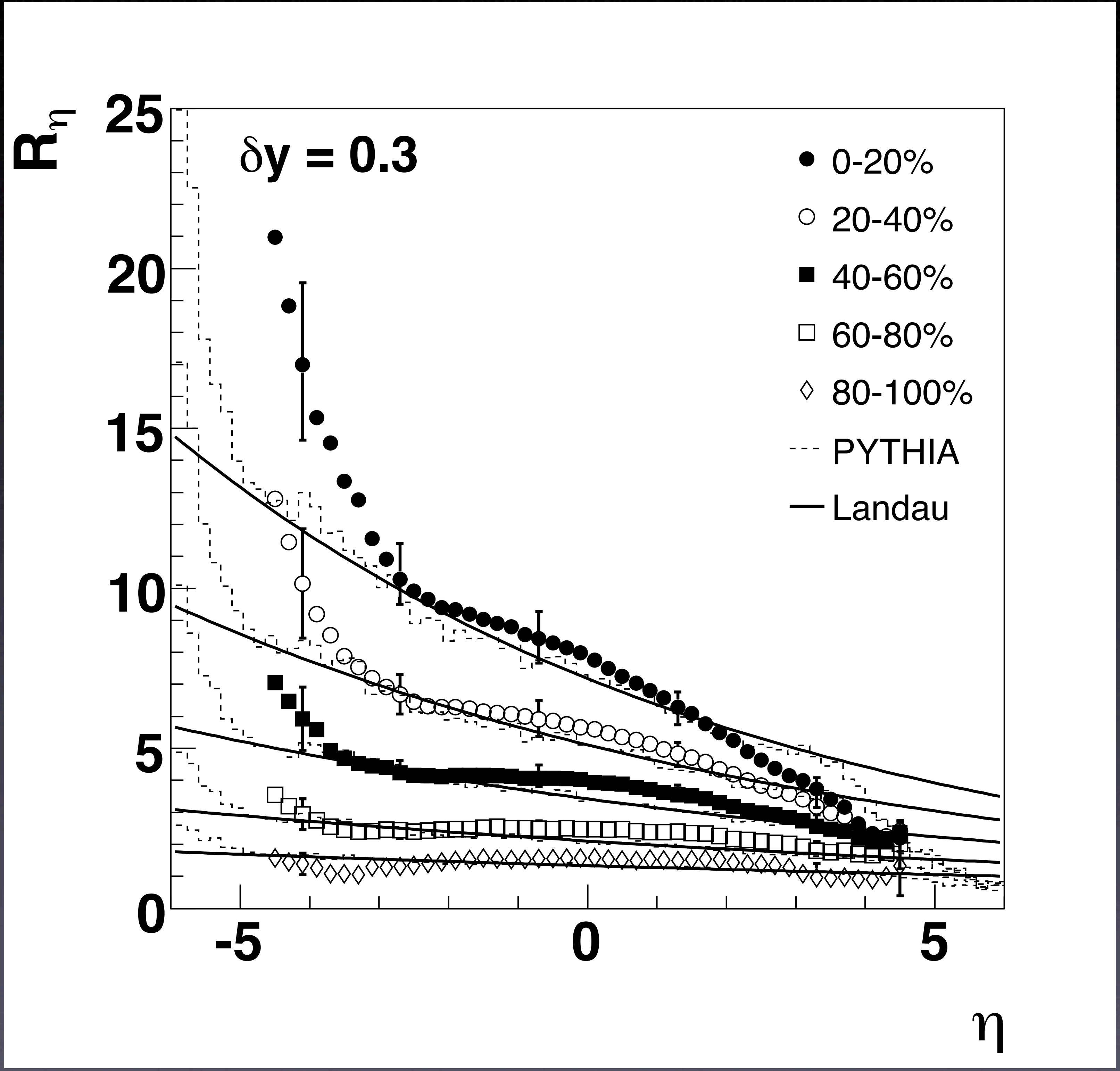
$$R_\eta = \frac{e^{-(y-\Delta y)^2/2L}}{e^{-y^2/2L}} \propto e^{-y\Delta y/L}$$

(for simplicity, <u>assume</u> $y=\eta$)

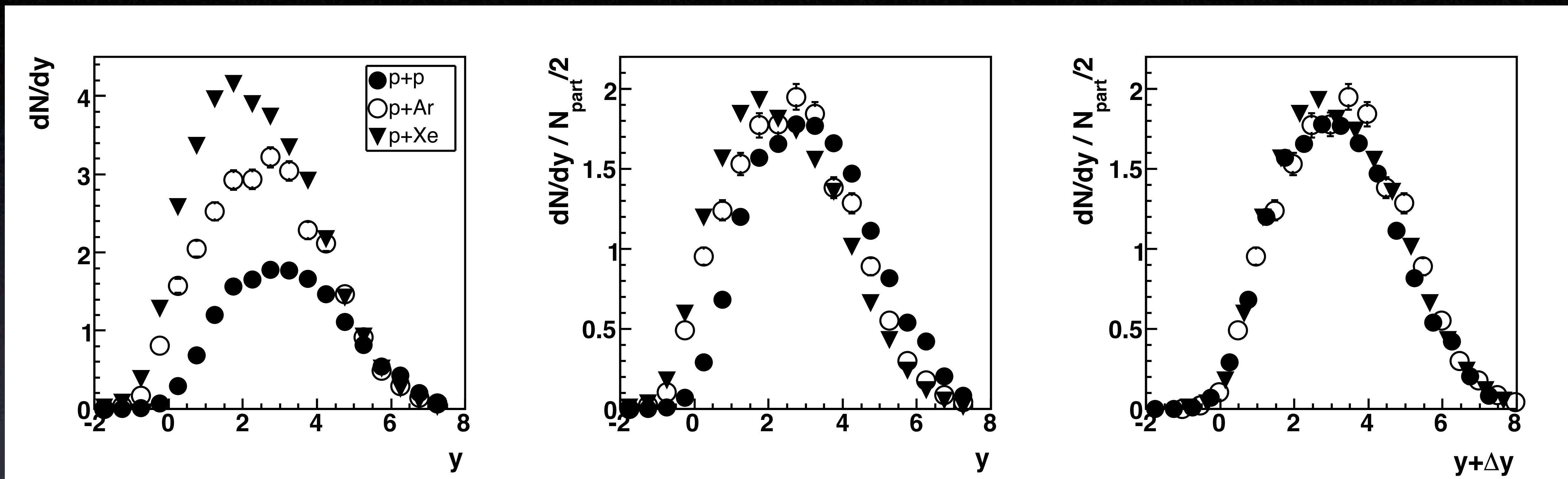
Comparisons to p+p



Comparisons to p+p

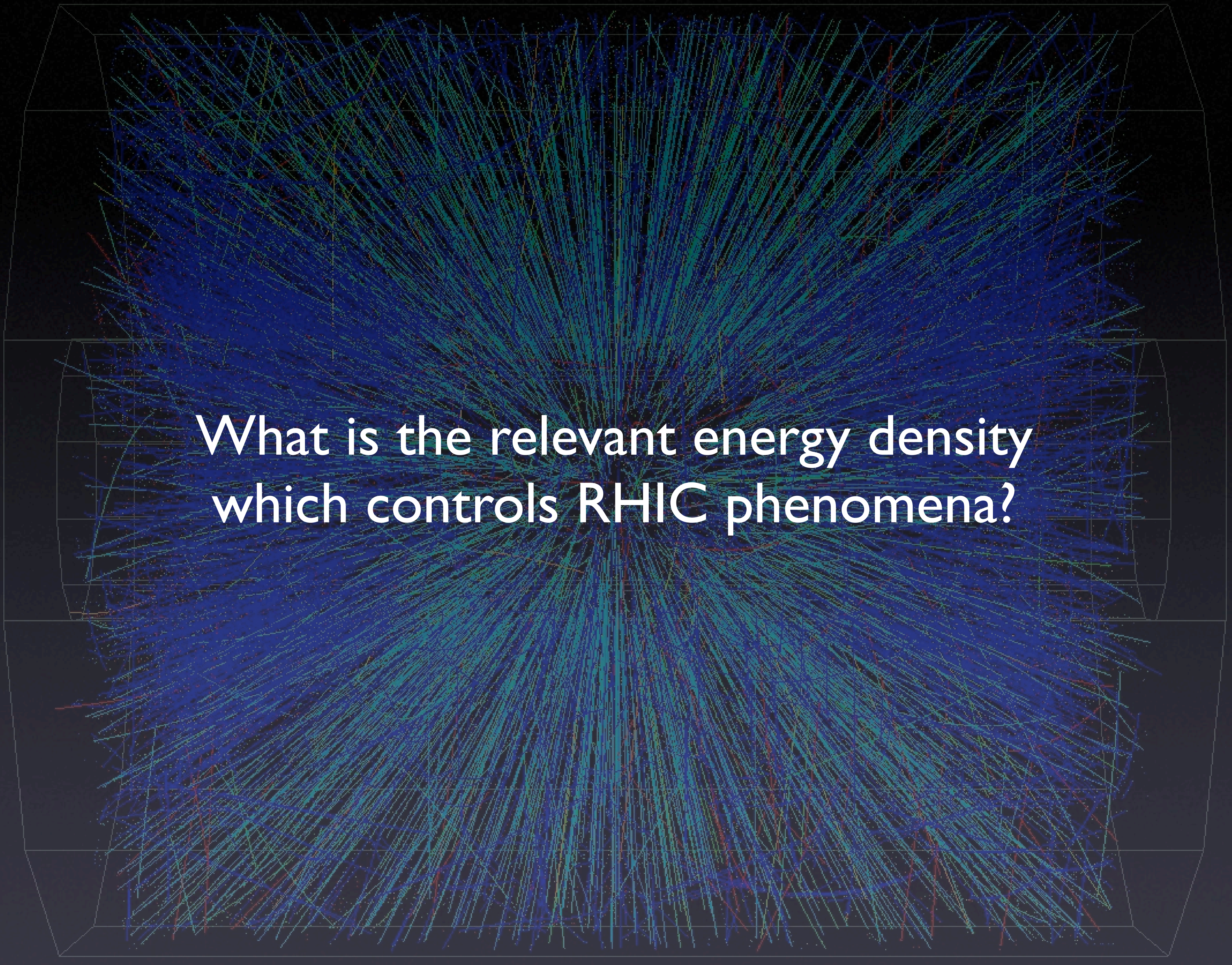


Lower Energy Data



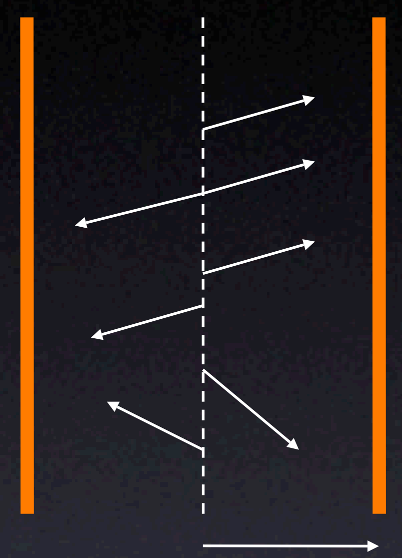
NA5 (1984) measured rapidity distributions in p+A collisions (p, Ar, Xe)

By dividing by $N_{part}/2$ and shifting by Δy, one can make the distributions overlap



What is the relevant energy density which controls RHIC phenomena?

Bjorken Density



$\Delta z = \Delta\beta\tau_F$

$$N = \frac{dN}{d\beta_L}\Delta\beta_L = \frac{dN}{dy}\frac{\Delta z}{\tau_F}$$

$$\varepsilon = \frac{E}{V} = \frac{N\langle E\rangle}{\Delta z \times A} = \frac{dN}{dy}\frac{\Delta z}{\tau_F}\frac{\langle m_T\rangle}{\Delta z \times A}$$

$$= \frac{dN}{dy}\frac{\langle m_T\rangle}{A\tau_F} = \frac{dN}{dy}\frac{\langle m_T\rangle}{\pi R^2\tau_F}$$

At low velocity $y \sim \beta$

Only particles with $\beta < z/t_F$ will be inside volume with half-length z

A very standard estimation of energy density in A+A collisions

Bjorken Estimates

p+p collisions

$$\epsilon_{pp} = \frac{dN}{dy}\frac{\langle m_T \rangle}{\pi R^2 \tau_F} \sim 0.4 \frac{GeV}{fm^3}$$

$\langle m_T \rangle$=0.4 GeV
τ=1 fm/c
R=0.9fm
dN/dy ~ 2.5

A+A collisions

$$\epsilon_{AA} = A\frac{dN}{dy}\frac{\langle m_T \rangle}{1.2 A^{2/3} \pi R^2 \tau_F} = \frac{A^{1/3}}{1.2}\epsilon_{pp}$$

If p+p and A+A had <u>same</u> dN/dy/(N_{part}/2) and <m_T>, expect a 5-6x higher energy density by construction. Real parameters give a factor of >10x.

If Cu+Cu and Au+Au collisions had <u>same</u> values, expect 50% difference in energy density!

Landau/Fermi Density

p+p collisions

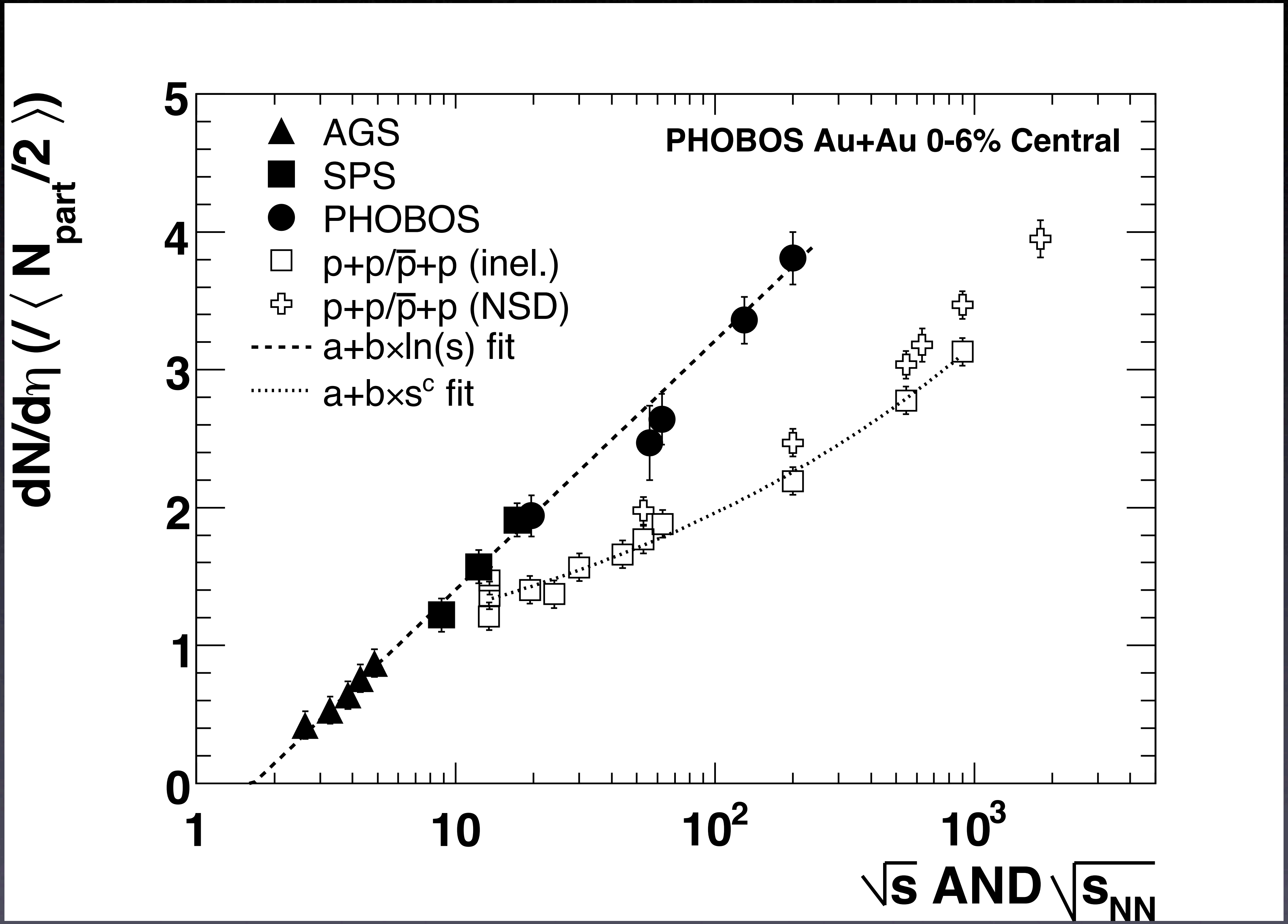
$$\epsilon_{pp} = \frac{E}{V} = \frac{\sqrt{s}}{V_0}\left(\frac{\sqrt{s}}{2m}\right) = \frac{s}{2mV_0}$$

A+A collisions

$$\epsilon_{AA} = \frac{E}{V} = \frac{A\sqrt{s}}{AV_0}\left(\frac{\sqrt{s}}{2m}\right) = \frac{s}{2mV_0} = \epsilon_{pp}$$

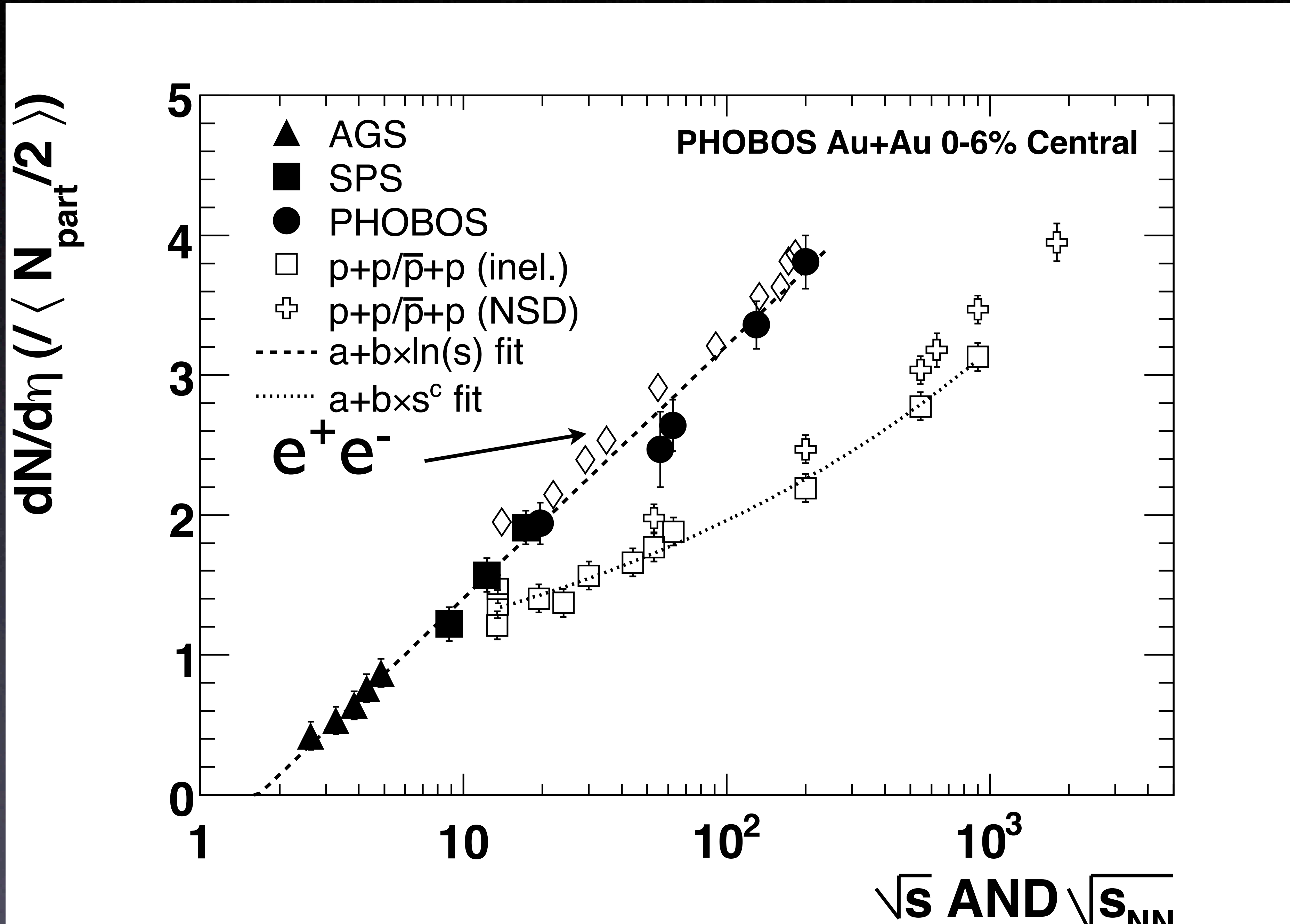
In Landau-Fermi model, no difference in energy density between Cu+Cu and Au+Au, and scales to same density in p+p
(but real p+p at full overlap would be <u>higher</u>)

Energy Density?



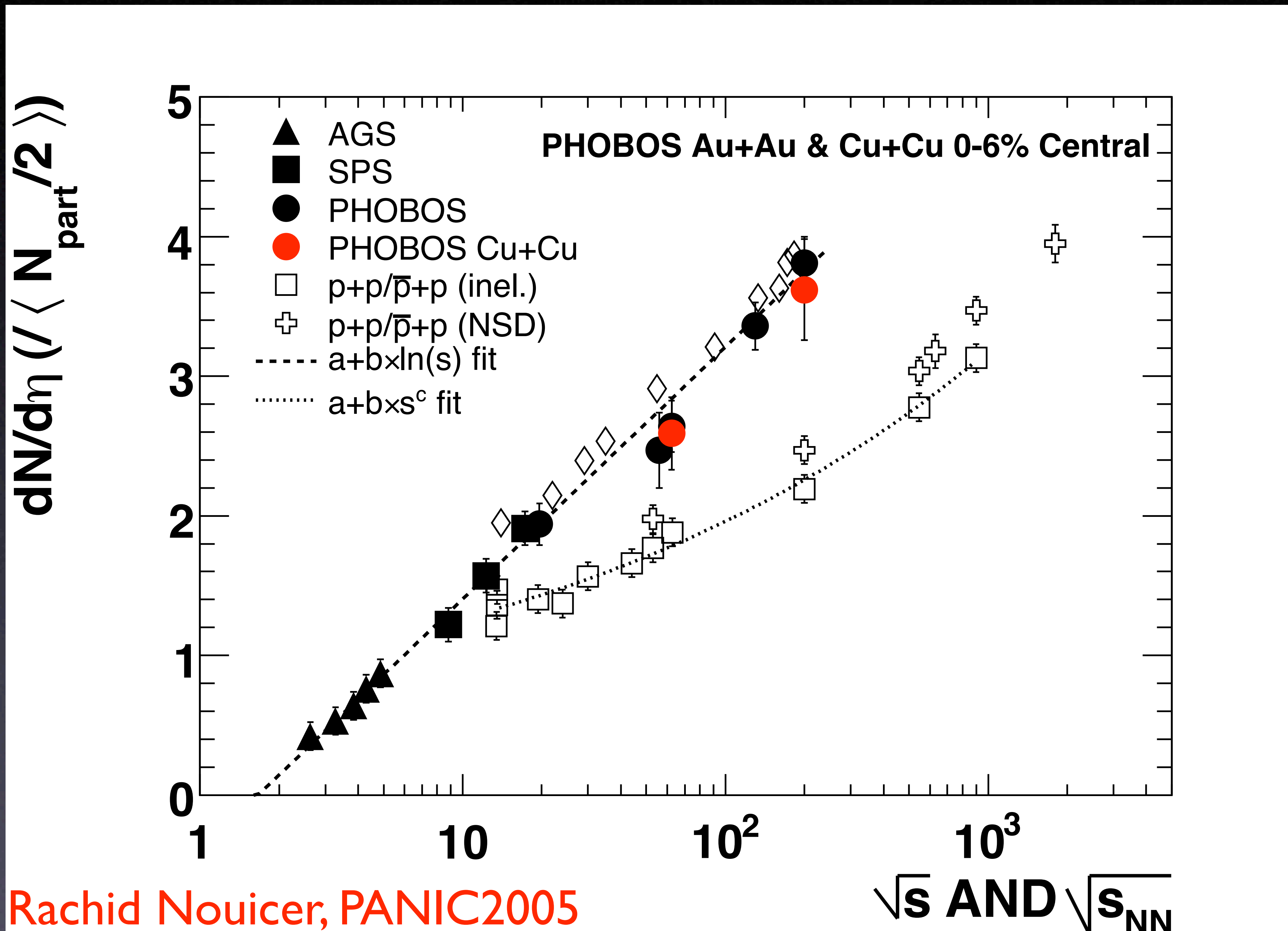
Consider this plot as a diagnostic for energy density

Energy Density?



e+e- multiplicities (peak of dN/dy_T) fit a similar trend

Energy Density?



Cu+Cu ~ Au+Au ~ e^+e^-

Should we get different ϵ from the same particle density?

Conclusions

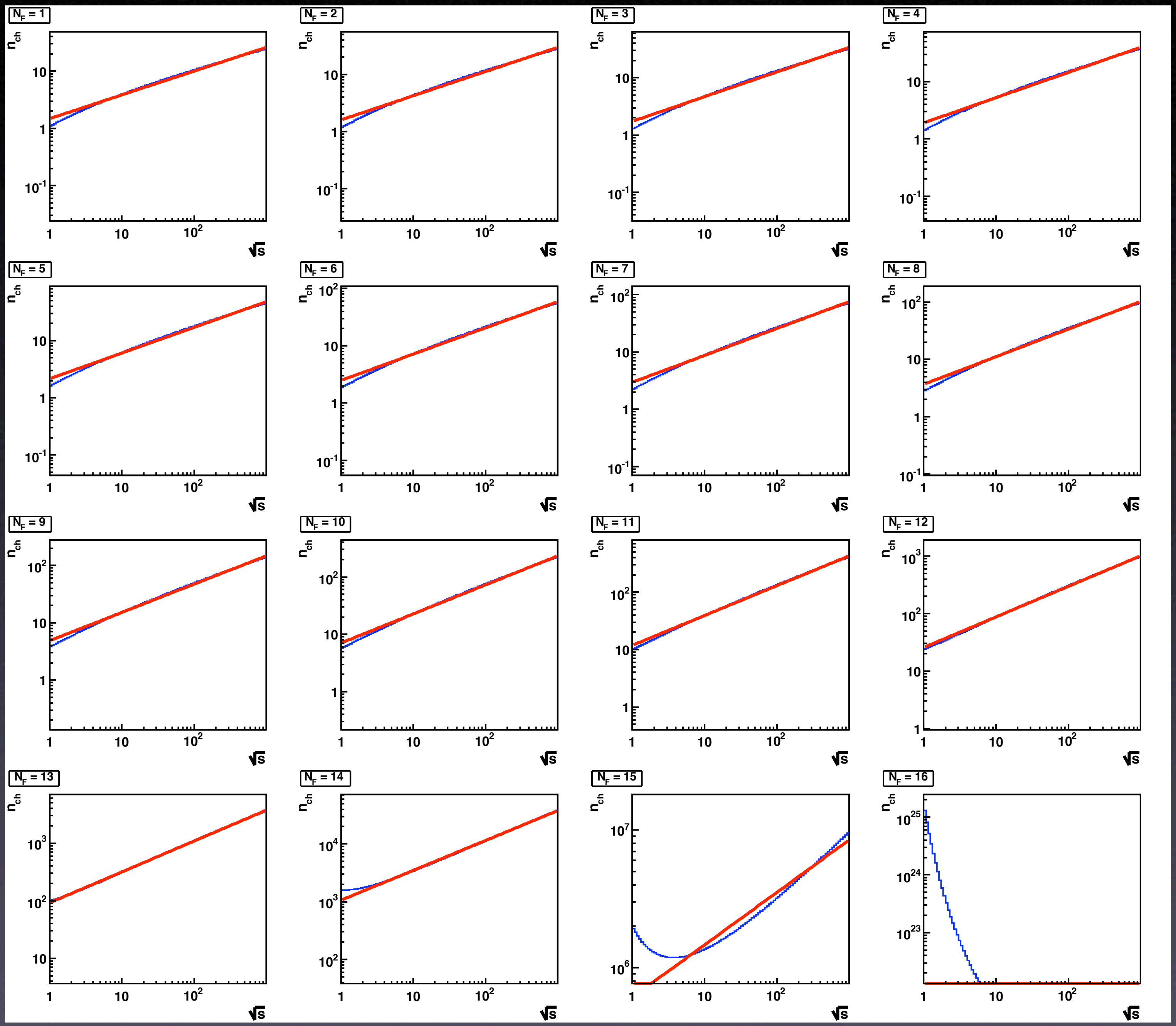
Various features of A+A, d+Au, p+p AND e+e-
may well be understood by
an extremely rapid local thermalization

Entropy production
Longitudinal Flow
Transverse Flow

Even pQCD "looks & acts" like Landau hydro

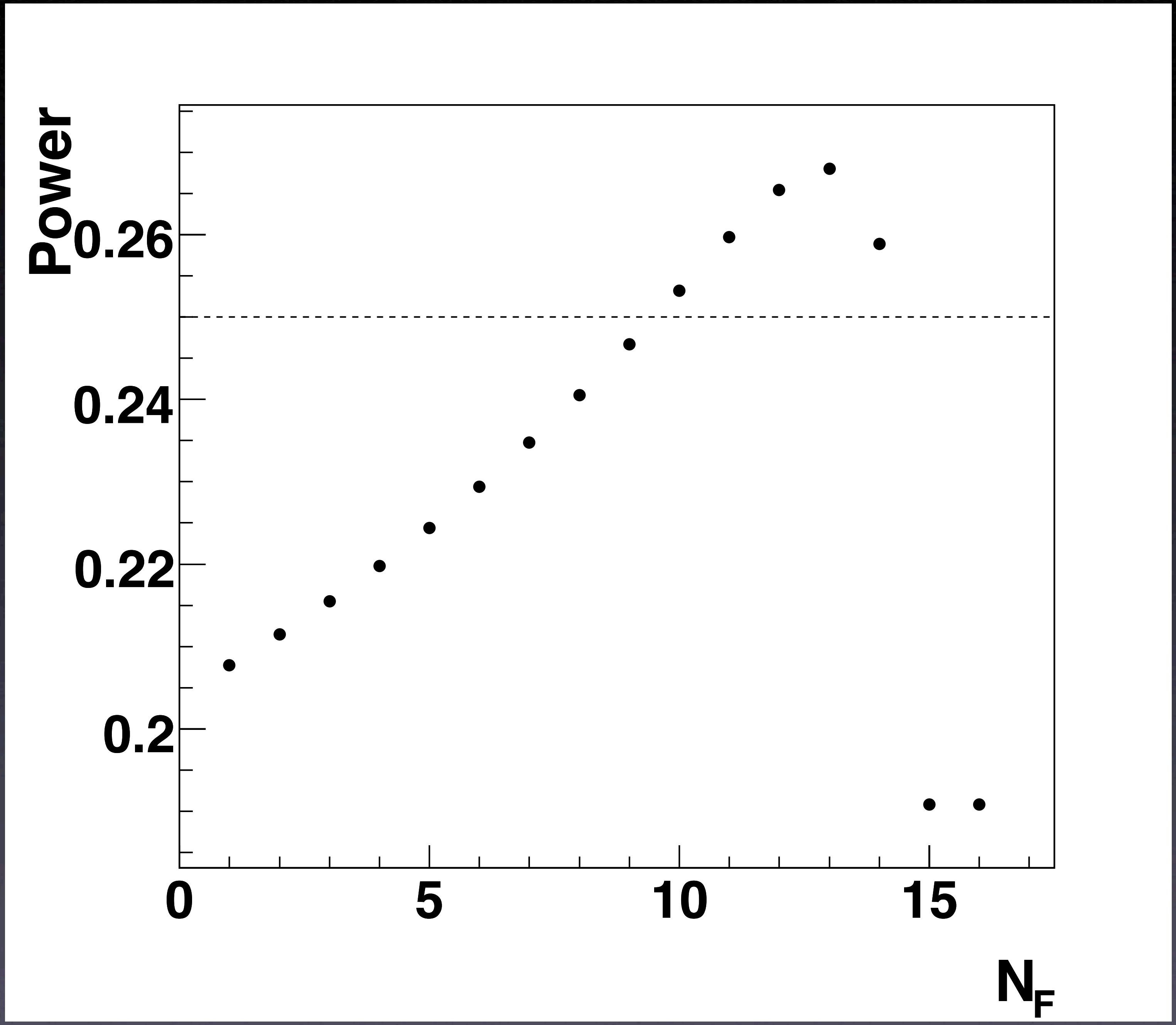
How will we understand this at a fundamental level?

pQCD vs. Power Law vs. N_F



QCD formula approaches powerlaw as one changes N_F, the number of active fermions

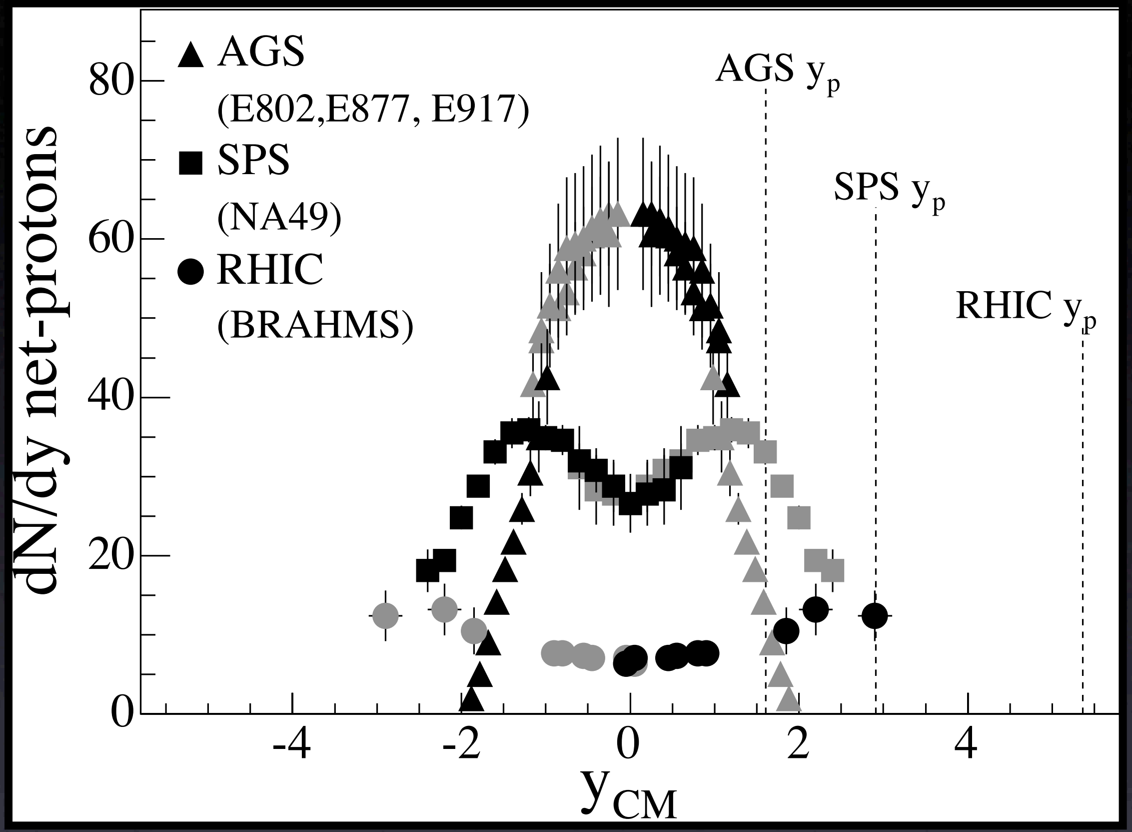
Power Law vs. N_F

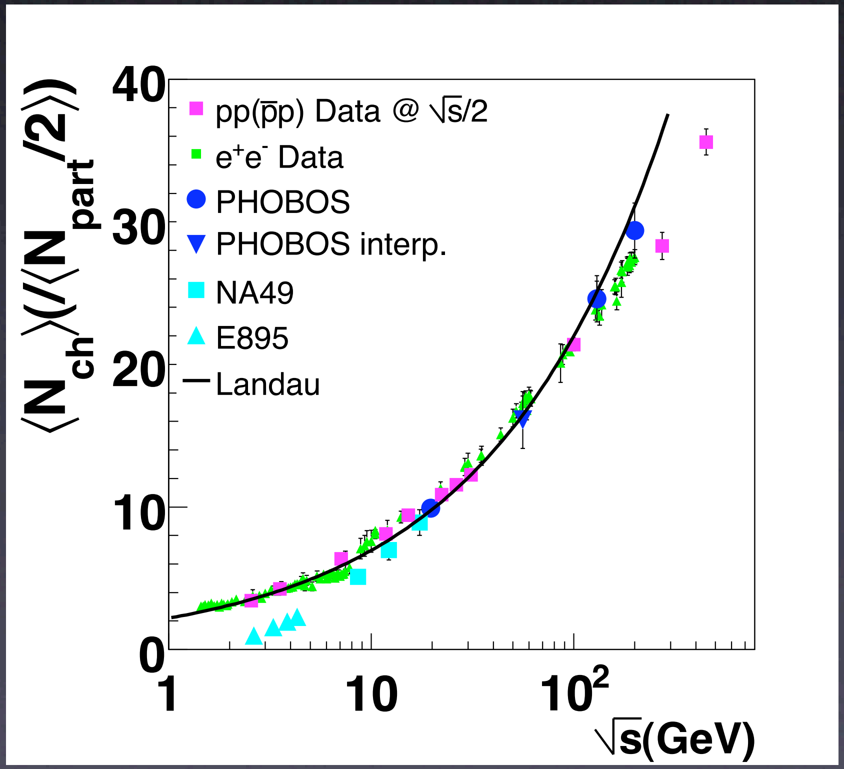


Interestingly, pQCD approaches and exceeds Landau-Fermi power law exponent!

A Contradiction?

Baryons do not seem to pile up at mid-rapidity as the energy gets higher

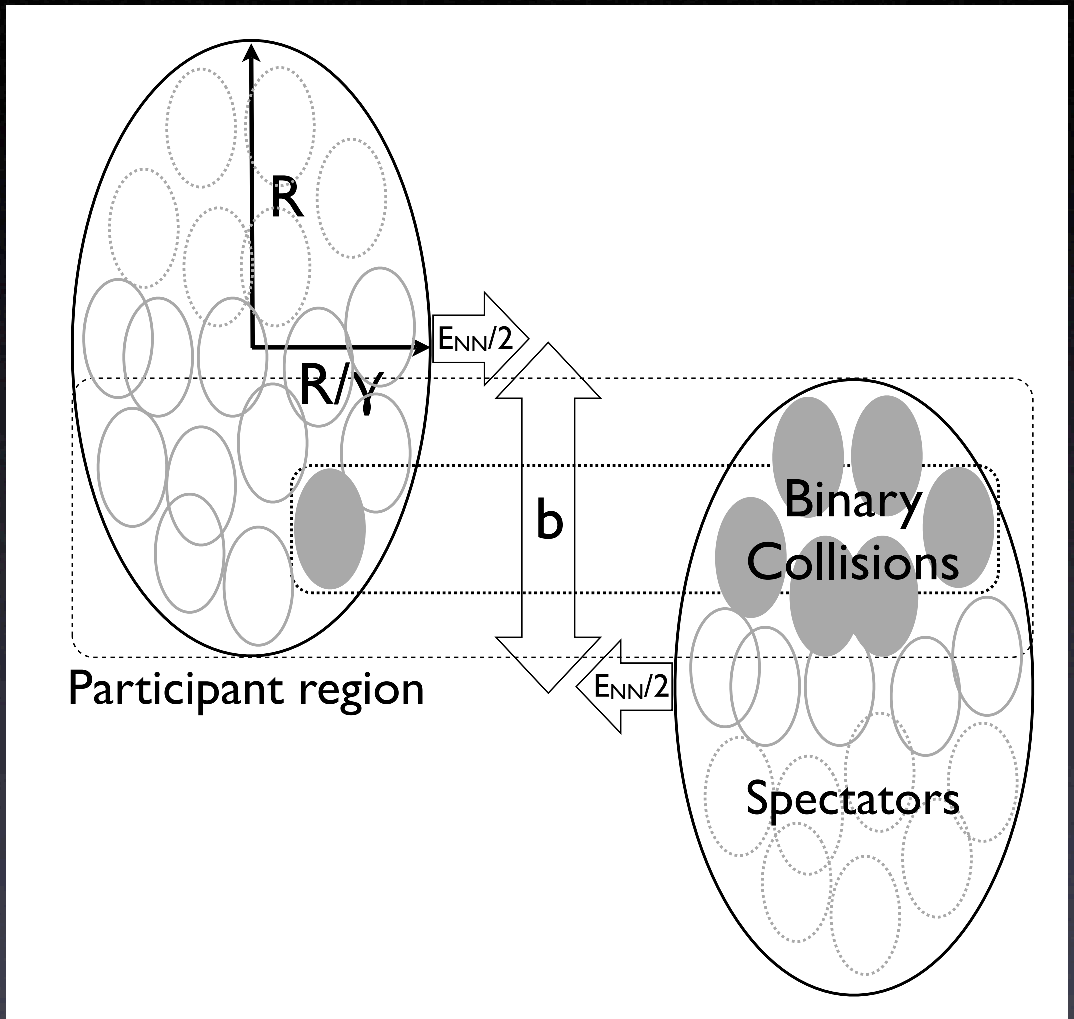


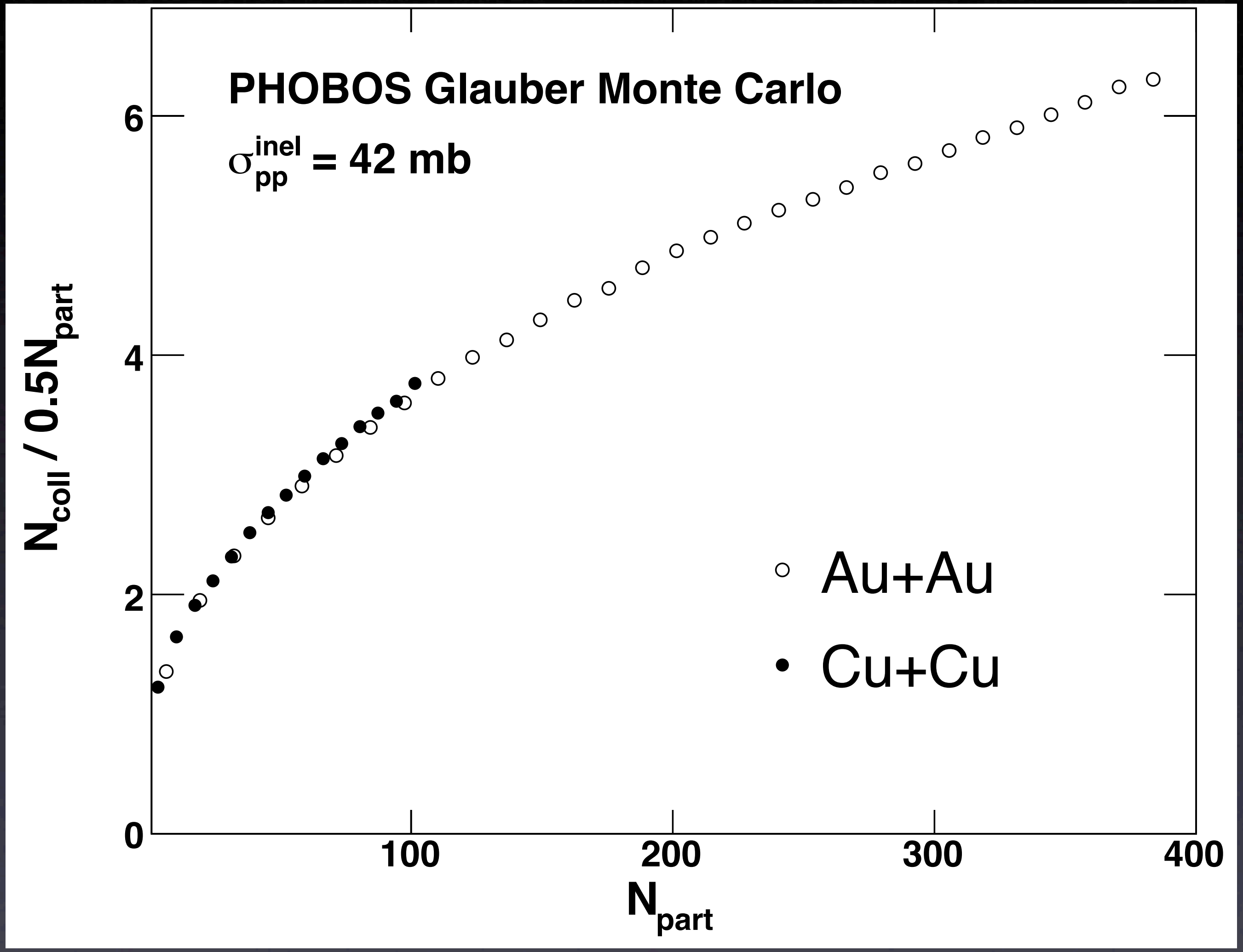


e+e- systematics suggest that the leading particle effect is gone (perhaps completely)

How could the leading particles lose all their energy, but not be "stopped"?

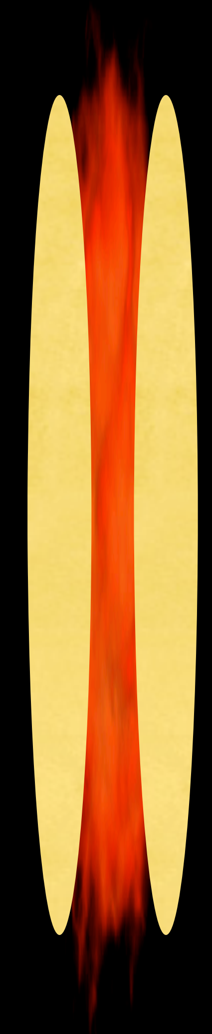
A Resolution?





Single collisions deposit <u>1/2</u> the energy
The rest of the energy must be deposited in <u>subsequent collisions</u> of each nucleon

A Resolution?

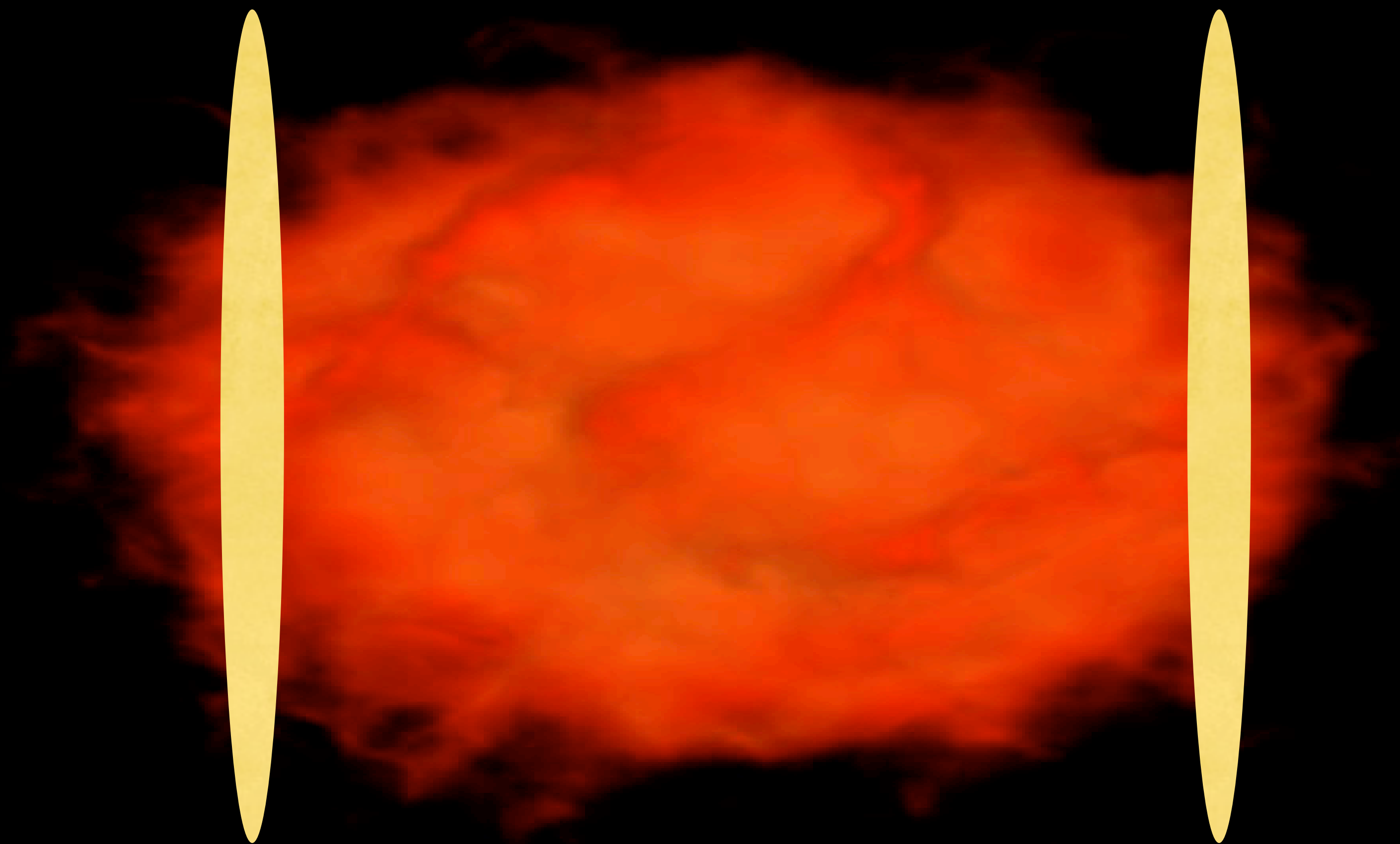


Maybe baryons stop in two “clumps” displaced from Z=0

Huge energy density pushes outward

Would accelerate baryons to large rapidities!

A Resolution?



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“Leading Particles” in e+e-

SLAC–PUB–8160
June 1999

A STUDY OF CORRELATIONS BETWEEN IDENTIFIED CHARGED HADRONS IN HADRONIC Z^0 DECAYS*

The SLD Collaboration**
Stanford Linear Accelerator Center
Stanford University, Stanford, CA 94309

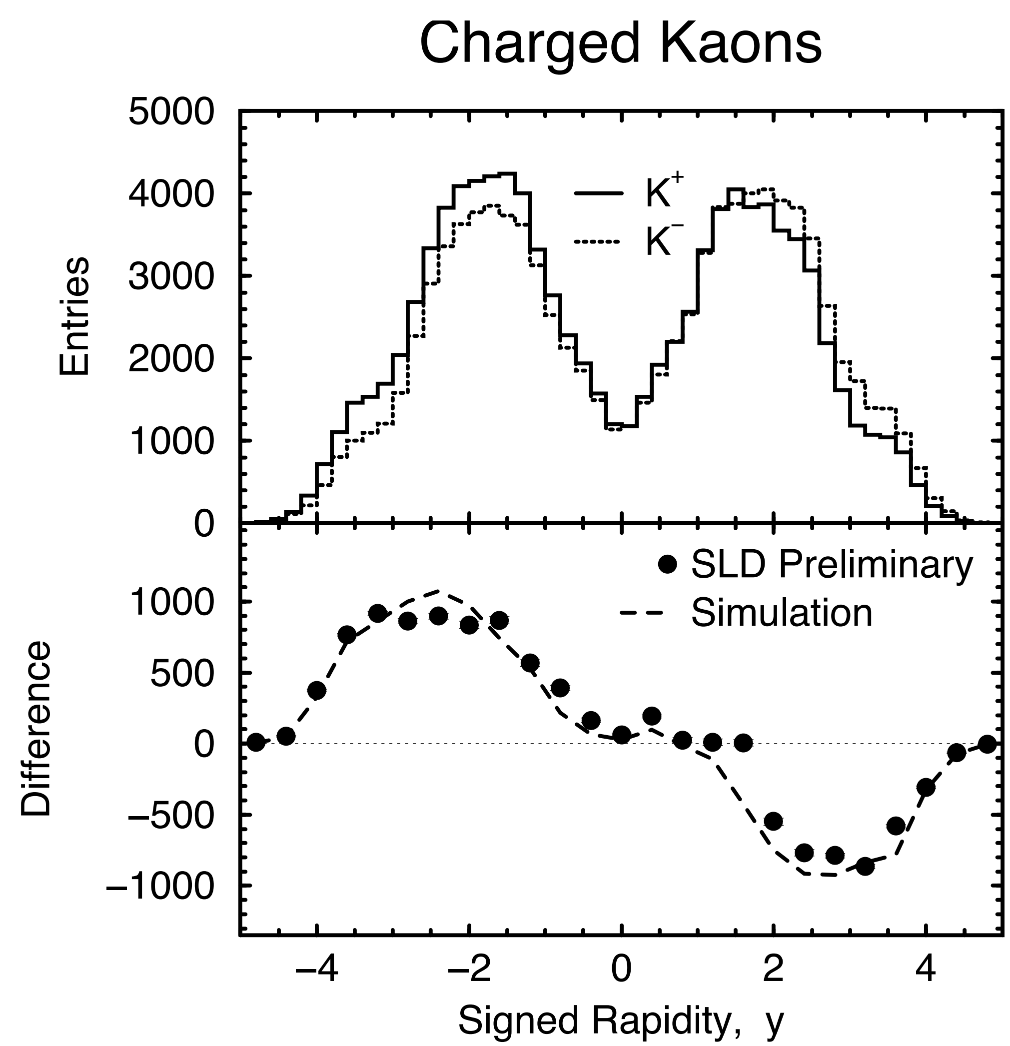

Figure 7: Distributions (top) of the rapidity with respect to the signed thrust axis for positively (histogram) and negatively (dashed histograms) charged kaons. The difference (bottom) between these two distributions compared with the prediction of the Monte Carlo simulation.